HTE Stack Manufacturing Cost Analysis

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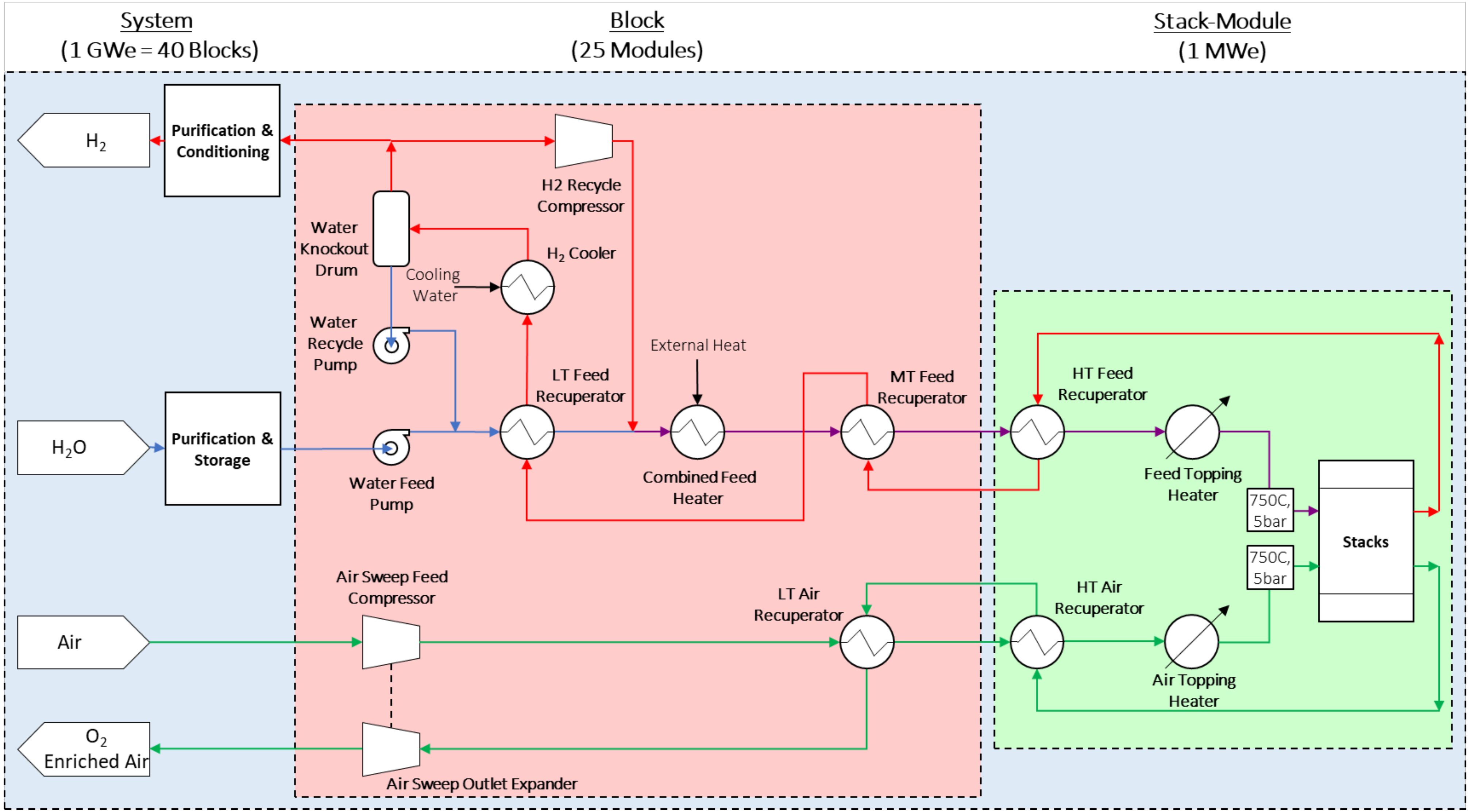
Outline

- System-Level Vision
- Solid Oxide Electrolysis Cells
- DFMA Cost Estimation Methodology
- Major Assumptions
- Solid Oxide Electrolysis Stack Cost Results
- Possible Pathway to Lower Stack Cost

SOEC SYSTEM DIAGRAM

Modules/Blocks/System: To take advantage of Economies of Physical Scale & Manufact. Rate



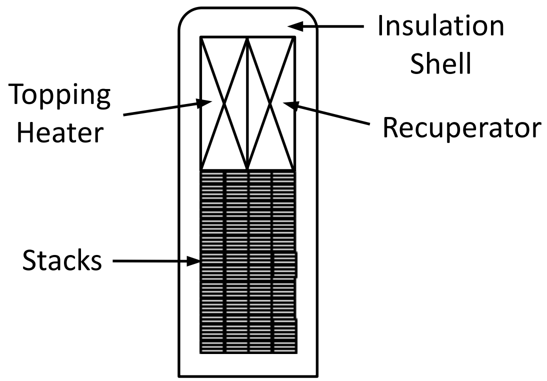
STACK-MODULE CONCEPT

Factory-built, Mass-Produced Modules & Module Skids

Non-Pressurized/Amb. Pressure Stack-Module Concept (Insulated Only)

Non-Pressure Containing:

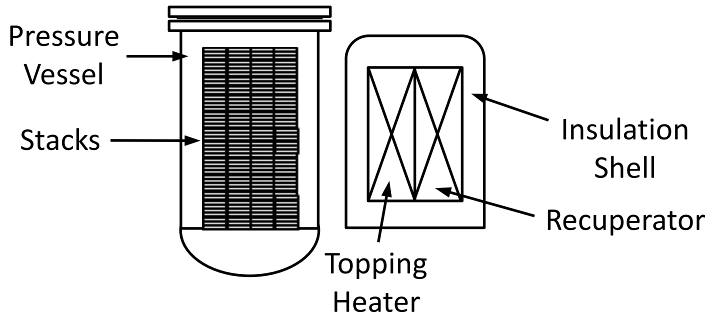
- **Stacks (20-100 x 50kWe stacks)**



Pressurized Stack-Module Concept 1 (External Thermal Equipment)

Pressure Vessel Containing:

- **Stacks (20-100 x 50kWe stacks)**

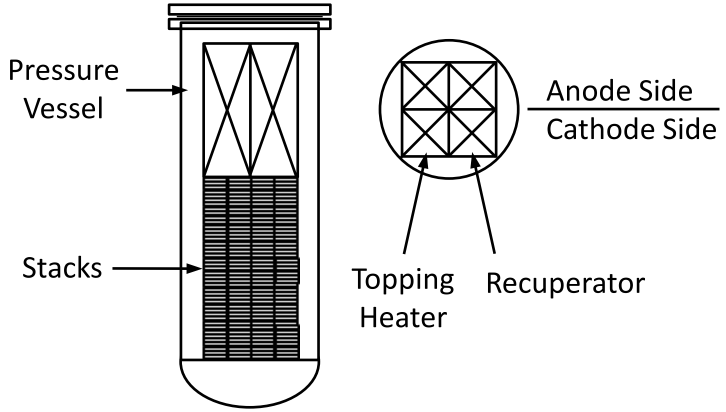


Non-Contained Recuperators & Topping Heaters

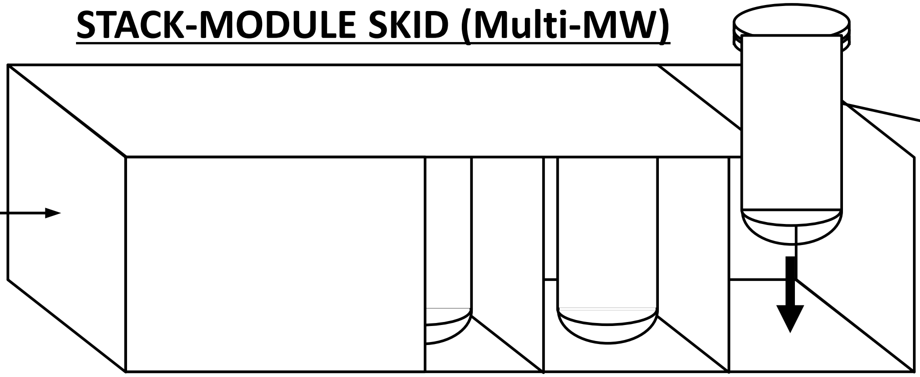
Pressurized Stack-Module Concept 2 (Internal Thermal Equipment)

Pressure Vessel Containing:

- **Stacks (20-100 x 50kWe stacks)**
- **HT Recuperators**
- **In-line Topping Heaters**



STACK-MODULE SKID (Multi-MW)



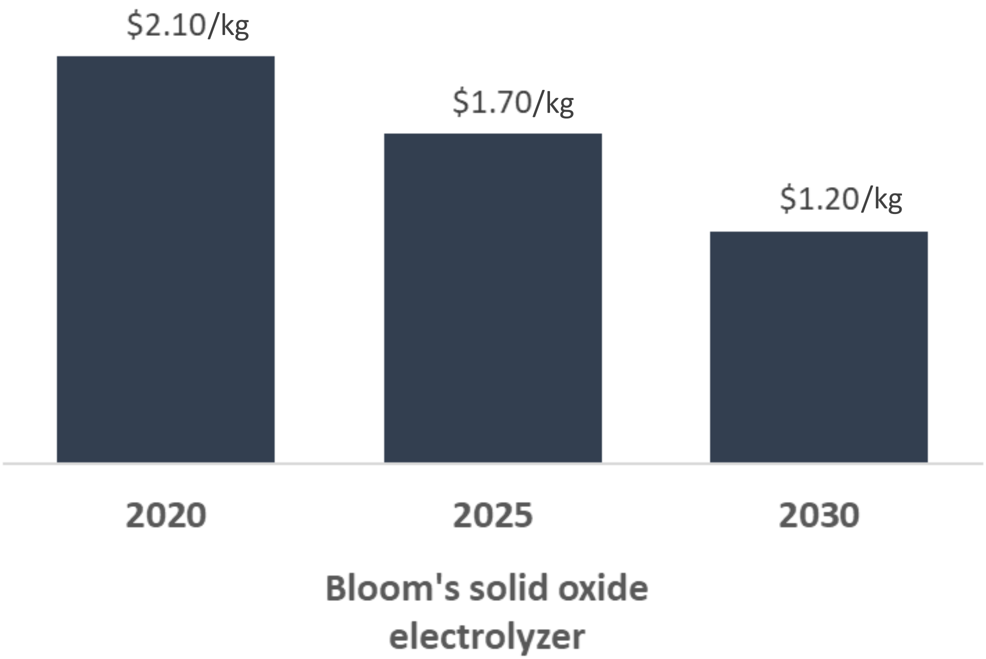
Housing/Enclosure/Container & Support Structure

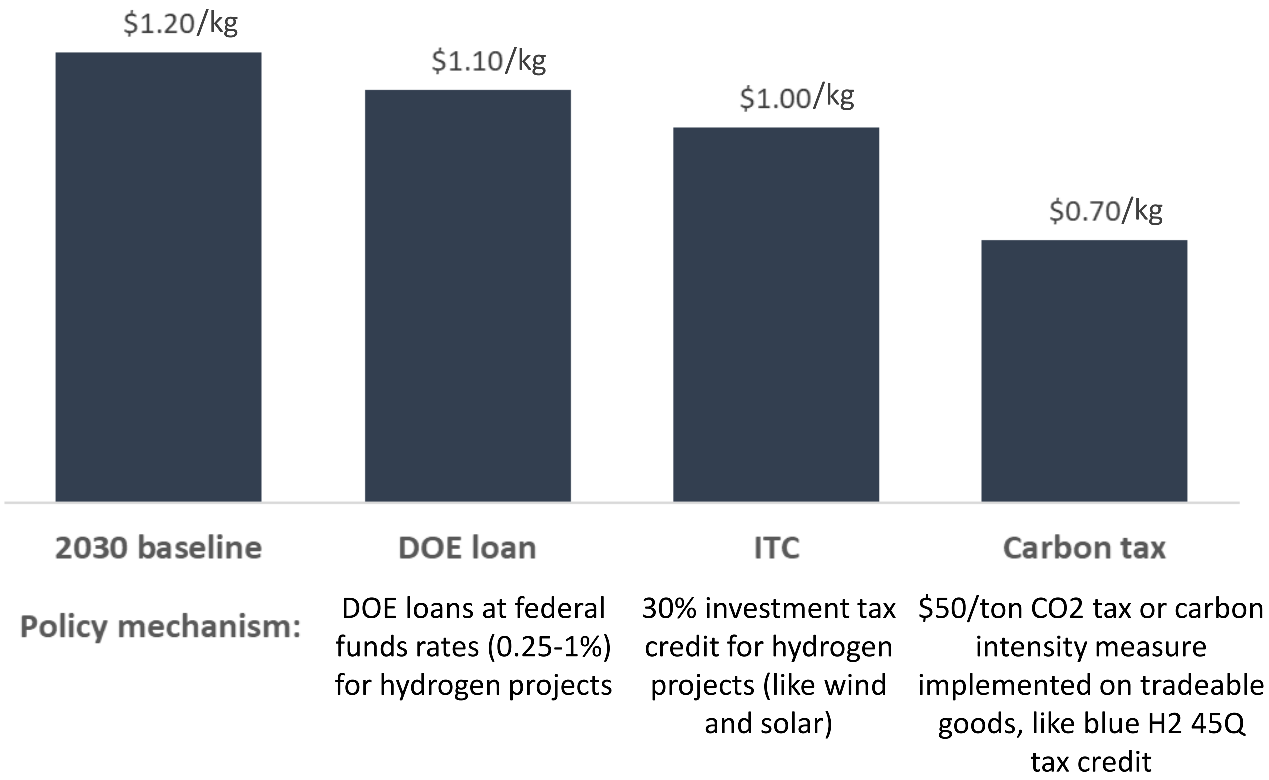
- Contains Multiple Stack Modules
- Contains All Stack-Module BOP
- Can be Explosion Proof or Intrinsically Safe

Stack-Module

- Pressure Containing
  - Internal Recuperators & Topping Heaters
  - External Recuperators & Topping Heaters
- Non-Pressure Containing

INDUSTRY PROJECTS PATH TO $1/KG
(Bloom Energy White Paper)





Potential for <$1/kg$H_2$ with:

- Low-cost electricity
- Waste heat integration
- Policy incentive
- Low capital cost, low/efficient company markup
- Low installation cost
- (Presumably) high manufacturing rate

Source: Bloom Energy (2021): The Role Of Solid Oxide Technology In The Hydrogen Economy: A Primer White Paper, May 2021.

SOEC COST & PRICE LANDSCAPE

DOE Stack Target is <$100/kW but ~$50/kW is likely required to achieve near $1/kgH$_2$

	Preliminary Estimates (2022)		Bloom Energy (2021)	
YEAR	**2022 (50MW/yr)**	**2030 (To achieve EarthShot Target))**	**2020**	**2030**
Total System Cost ($/kW) -- BOP Cost -- Stack Cost	$950/kW ~$700/kW ~$250/kW	$230/kW ~$150/kW ~$50/kW	$917/kW -- NA -- NA	$229/kW -- NA -- NA
System Price ($/kW)	$1,235/kW (30% markup)	$300/kW (30% markup)	$1,192/kW (30% markup)	$298/kW (30% markup)
Cost of Electricity ($/kWh)	$0.02	$0.015	$0.02	$0.014
Starting Efficiency (kWh/kg)	34.4 (stack) 39.8 (sys)	34.4 (stack) 37.1 (sys)	36.5 (stack)	36.5 (stack)
Capacity Factor	90%	90%	70%	50%
Cost of H2 ($/kg)	**~$2.84/kg**	**~$1.19/kg**	**$2.14/kg**	**$1.15/kg**

SOEC COST & PRICE LANDSCAPE

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Cost of H2 ($/kg)				

Consistent with IRENA 2050 Target*
<$200/kW (stack) a
<$300/kW (systen

*IRENA, "Green Hydrogen Cost Reduction: Scaling Up Electrolysers to Meet the 1.5°C Climate Goal", 2020.

DFMA Cost Estimation Methodology

- A **bottoms-up manufacturing cost analysis** approach used to build system production costs step-by-step
  - A product is broken down into constituent parts, and a specific design and fabrication procedure is conceptualized for each component
  - Raw material and processing costs for each component and step are calculated using an Excel-based model that considers material, equipment, tooling, labor, energy, markup (if necessary), and financial costs.
- Provides insights into both high-cost materials and processes and what cost targets are feasible at current device or system performance levels
- Optimal manufacturing cost of an SOE stack in annual total or normalized expenditures in \$/kW (DC stack input) or \$/cm^2 of total SOE cell area

Major Stack Parameter & Cost Estimation Assumptions

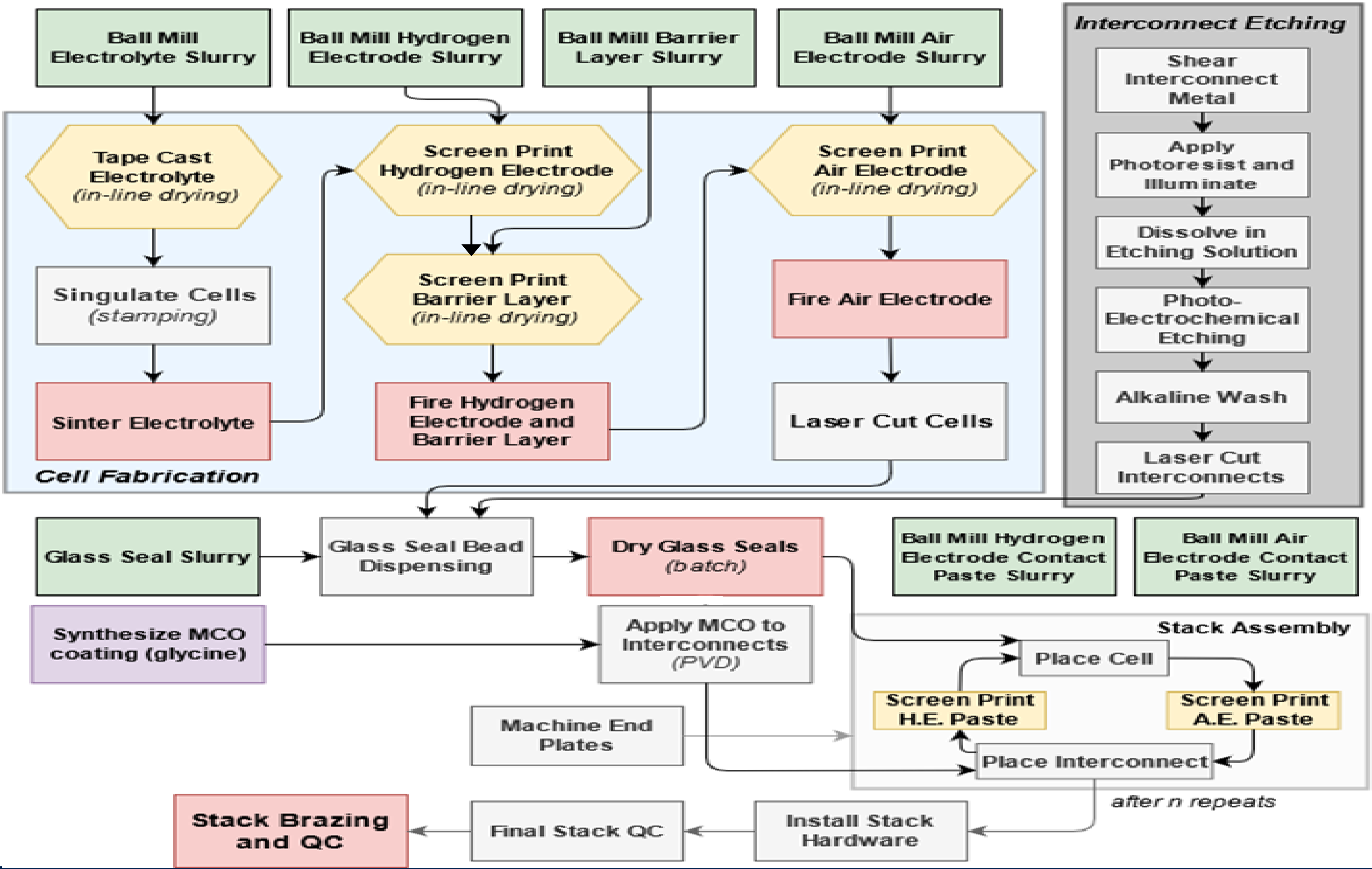
Parameter	Unit	Default Model Values
Annual Production Rate	MW/year	25 / 50 / 75 / 100 / 200 / 350 / 500 / 650 / 825 / 1,000 / 1,150 / 1,300 / 1,450 / 1,600 / 1,800 / 2,000
Stack Rated DC Power Input	kW_{DC}	50
Cell Construction	--	Electrolyte Supported / Hydrogen-Electrode Supported
Cell Operating Voltage	V/cell	1.285 (thermo-neutral)
Cell Current Density	mA/cm^2	900 / 1500*
Cell Power Density	W/cm^2	1.157 / 1.928
Stack Oversizing for Degradation	%	10%
Cell Size	cm x cm	15 x 11
Cell Active-to-Total Area Percentage	%	60%
Cell Active Area	cm^2/cell	99

*Based on 48 5-day working weeks (240 total days) per year with two 8-hour (7-hour productive) shifts per day for a total of 3,360 hours per year (h/year).

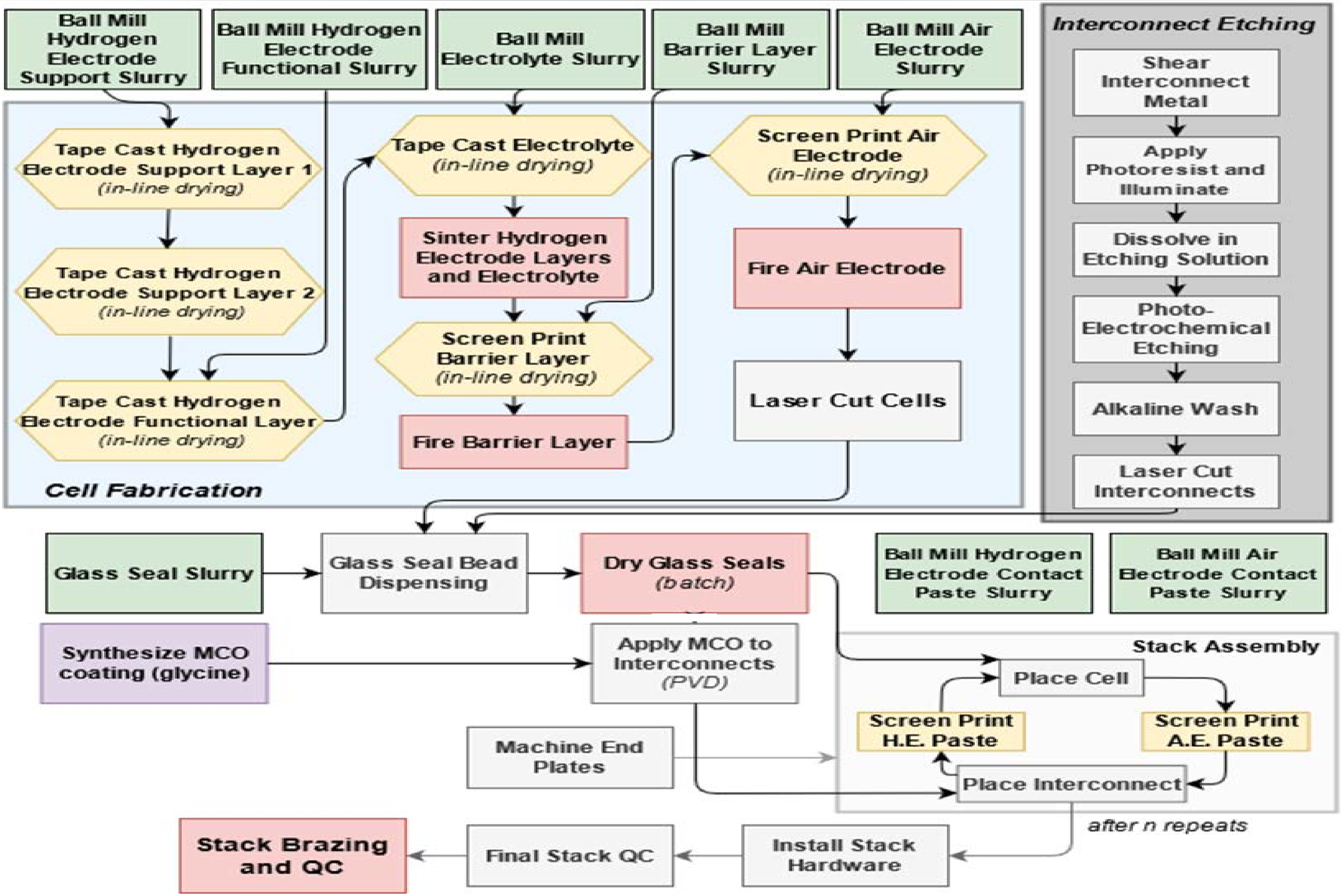
SOE Cell Stack Material Assumptions

Component/Layer	Electrolyte-Supported Cells		Hydrogen Electrode-Supported Cells	
	Material	Thickness (μm)	Material	Thickness (μm)
Hydrogen Electrode Support Layer (Cathode)	N/A	N/A	NiO / 3-YSZ	**280**
Hydrogen Electrode Functional Layer (Cathode)	NiO / 8-YSZ	25	NiO / 8-YSZ	20
Electrolyte	10-SSZ	**125**	8-YSZ	**10**
Barrier Layer	GDC	10	GDC	5
Air Electrode (Anode)	LSCF-GDC	25	LCSF-GDC	25
Cells per Stack	481		289	

Process flow diagram of "generic" SOE stacks fabrication using electrolyte-supported cells



Process flow diagram of "generic" SOE stacks fabrication using hydrogen electrode-supported cells



Key SOEC Manufacturing Processes

	Key Parameter/Attribute Affecting Cost	Other Parameter/Attribute Affecting Cost
Casting	Line speed Width	Capital Cost
Heat Treating	Number of Firings, Oven Size, Cycle time, Packing-Fraction/Plate-spacing, Yield	Capital Cost
Printing	Parts per cycle, Effective Cycle Time	
Sealing	Speed of application, Method of sealing (Heat Treat)	
Coating (e.g., MCO)	Method of application (PVD, thermal spray), Speed of Application	Post-application heat treatment
Plate Forming (Interconnects)	Method of Forming (stamping, laser cut), Cycle Time	Capital Cost

Other Processes

	Key Parameters/Attributes Affecting Cost
Ball Mill/Sifting	Batch Size Required particle distribution
Singulation/ Discretization	Type of Process: • Laser cutting: cutting speed • Stamping: scoring, speed
Machining (endplates)	Amount of material to be removed Extent of “near net-shape” in forming process
Stack Assembly	Number of discreet parts to be placed Placement Accuracy required Handling difficulties (wet contact paste, fragile, difficult to grasp)
Etching (interconnects)	Etching-Time Depth-of-Etch Batch size

Typical Heat-Treating Steps

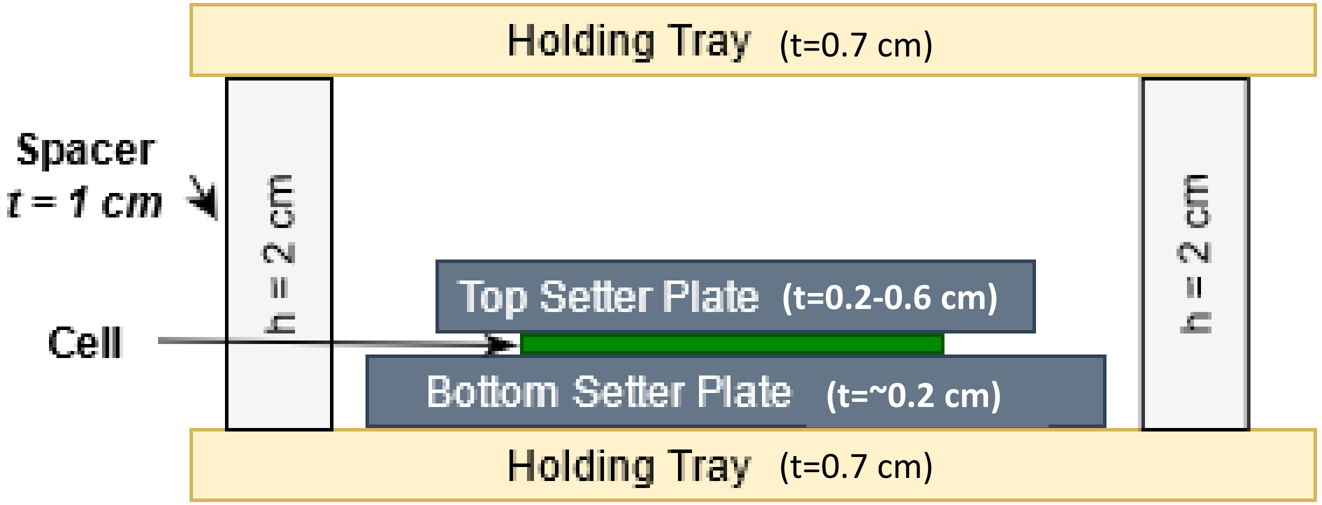
(Five separate Furnace Operations modeled in baseline systems)

Cell Construction	Firing	Maximum T (°C)	Total Cycle Time (h)	Gas Environ.	Oven Type	Notes
ESC		~1400	30		S/M/L Pusher Kiln	
		1200	18.4			
		1075	11.4			
HSC		~1400	30			
		1200	18.4	Air		
		1075	11.4	Air		
Both		200	4.9	Air	Batch	Batch furnaces
Both						

Co-Firing is a key cost reduction strategy

Pusher/Roller Kilns for High Volume

Ceramic Furniture Concept:



Tight Furnace Packing is a key cost reduction strategy but must not endanger Yield or Isothermal condition

Dimensions based on input from OneJoon (Germany)
(Specialists in Roller/Pusher Kilns & Furnaces for SOEC applications)

- Saggers (boats or carts) used to convey parts
- Top & Bottom Setter Plates used to reduce/eliminate part warpage: Bot. Plate (most applic.), Top Plate (only on 1st firing)
- Spacers used to allow adequate air-flow for temperature uniformity and off-gas removal
- Holding trays (holding multiple parts) and are stacked vertically (up to ~0.5-0.7 m kiln vertical height)
- Kiln furniture lifetime: ~450 cycles with SiC/RxSC

Multi-cell firing (bundles of co-fired stacked cells without separators) would be an impactful cost reduction strategy

Pusher Kiln Specifics

Parameter	Units	Small	Medium	Large
Total Capital Cost (1400 °C maximum)	$	$1,079,989	$1,411,603	$4,720,840
Total Capital Cost (<1250 °C maximum)	$	$861,242	$1,100,282	$4,161,672
Number of parallel saggers in each furnace	#	1	2	4
Heated Cross-Sectional Area	cm^2	1,550	3,100	6,200
Heated Length	m	10.5	10.5	24.4
Power Consumption	kW	45	90	418
Loading & Unloading Robots Required	#	2	2	4
Laborers (FTE) during operation	#	0.25	0.25	0.25

- **Based on price quotes from a US-based provider. Some details are withheld as proprietary.**
- **Parallel saggers used to increase capacity**
- **High temperature (1400C) about 115-25% higher cost then medium temperature (<1250C)**
- **Robots used for loading and unloading of parts**
- **At 2MW/year SOEC, 4 “large” pusher kilns are needed for Electrolyte Densification**

Key features affecting cost:

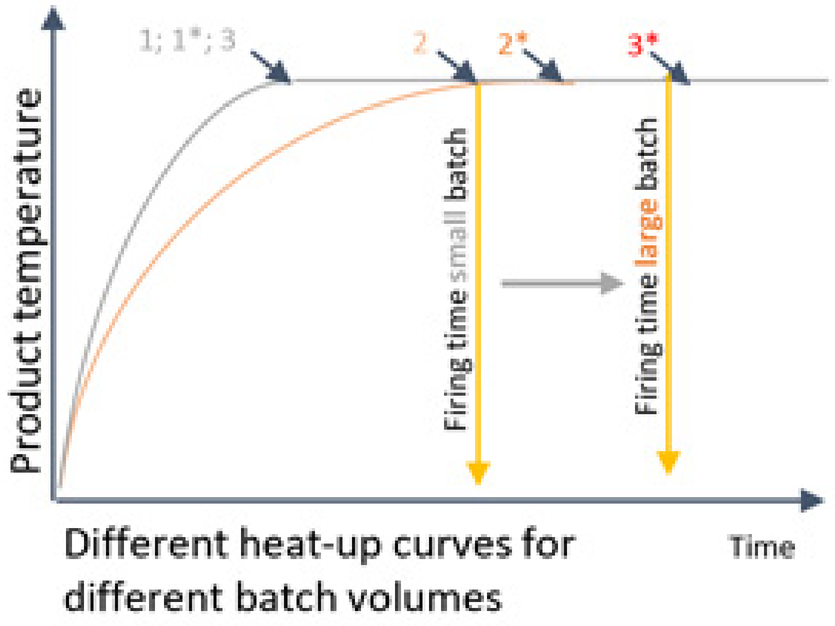
- Peak temperature
- # of lanes
- Length
- Vertical height of isothermal zone
- Atmosphere
- Gas tightness
- Sluice/Double-door locks

Batch Furnaces Can be Economic if Large and Tightly Packed

But require longer cycle times than continuous furnaces

Parameter	Units	Small Box Furnace	Large Box Furnace
Total Capital Cost	$	$122k	$660k
Heated width	cm	17.8	152
Heated length	cm	12.7	279
Heated height	cm	84	152
Average Power Consumption	kW	1.2	100
Estimated Part Yield	%	99.8%	99.8%

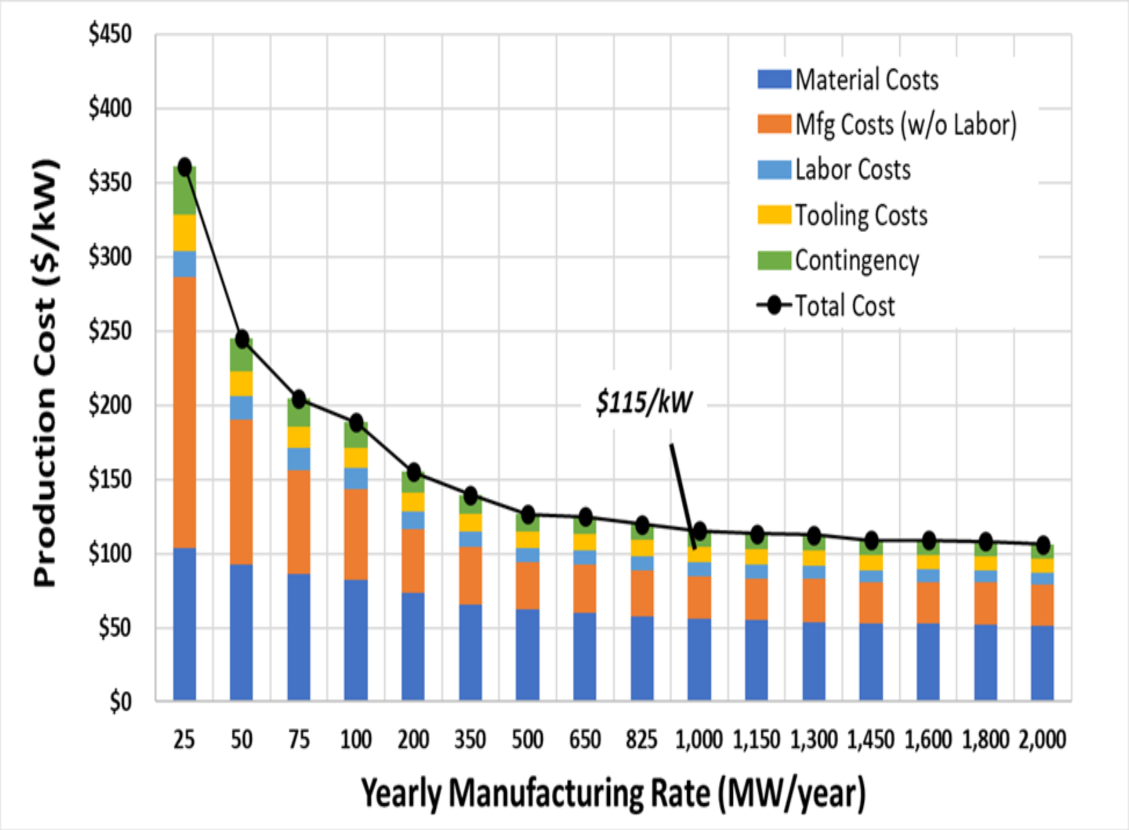
Scaling of batch furnaces requires lengthened cycle times to raise parts to temperature

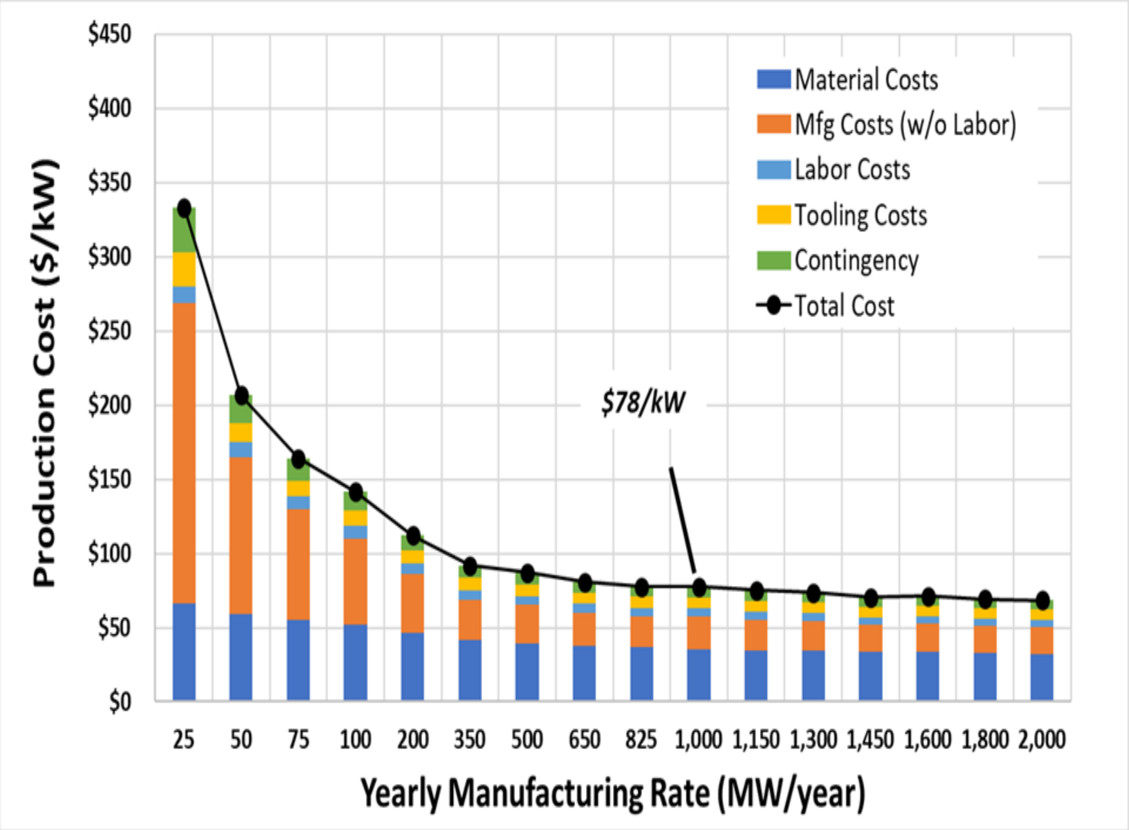


Source: OneJoon https://www.onejoon.de/en/markets-materials/sinter-ceramics-and-metals/sofc-soec-scaling-from-batch-to-continuous-series-production/

- **Can achieve a competitive cost per part**
- **Like Pusher Kilns, tight parts packing is a key factor in cost reduction**

SOE TOTAL STACK COST





Electrolyte-supported Cells (EsC)

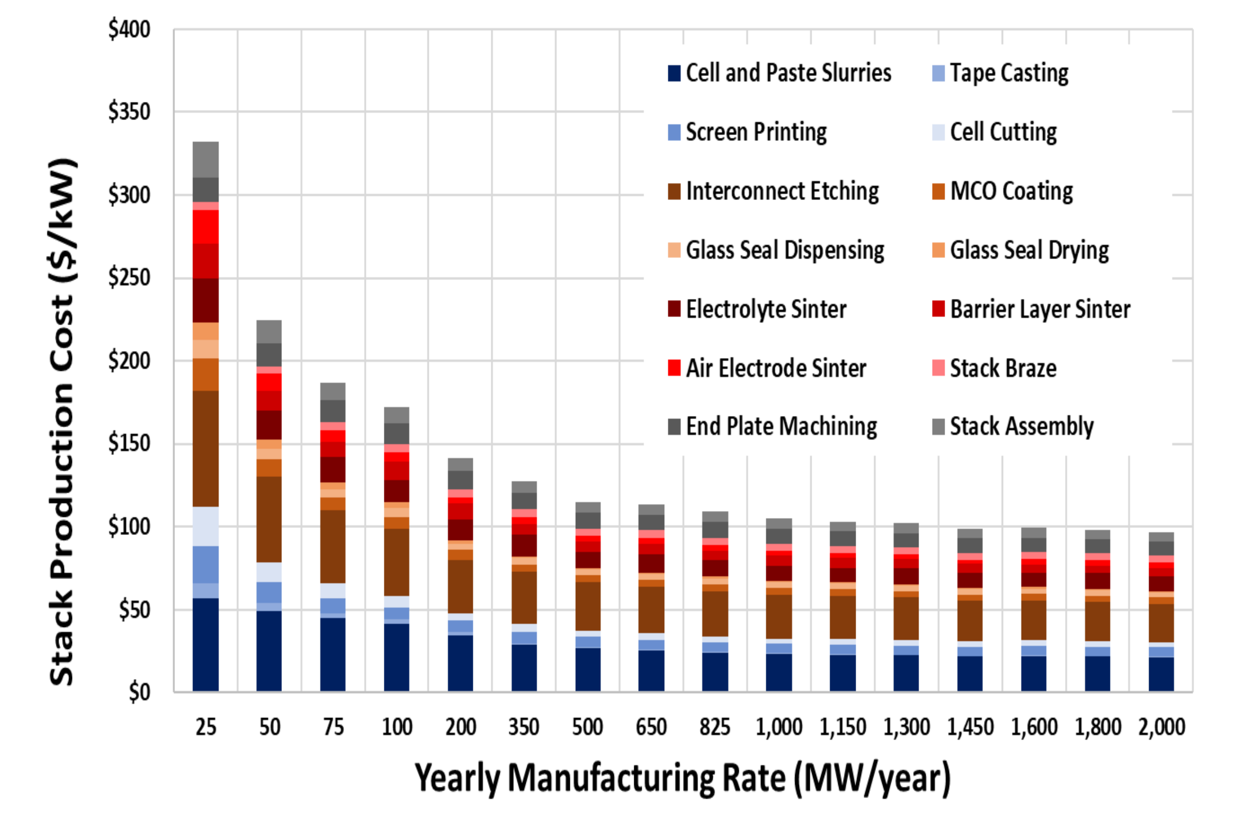
H_2 Electrode-supported Cells (HEsC)

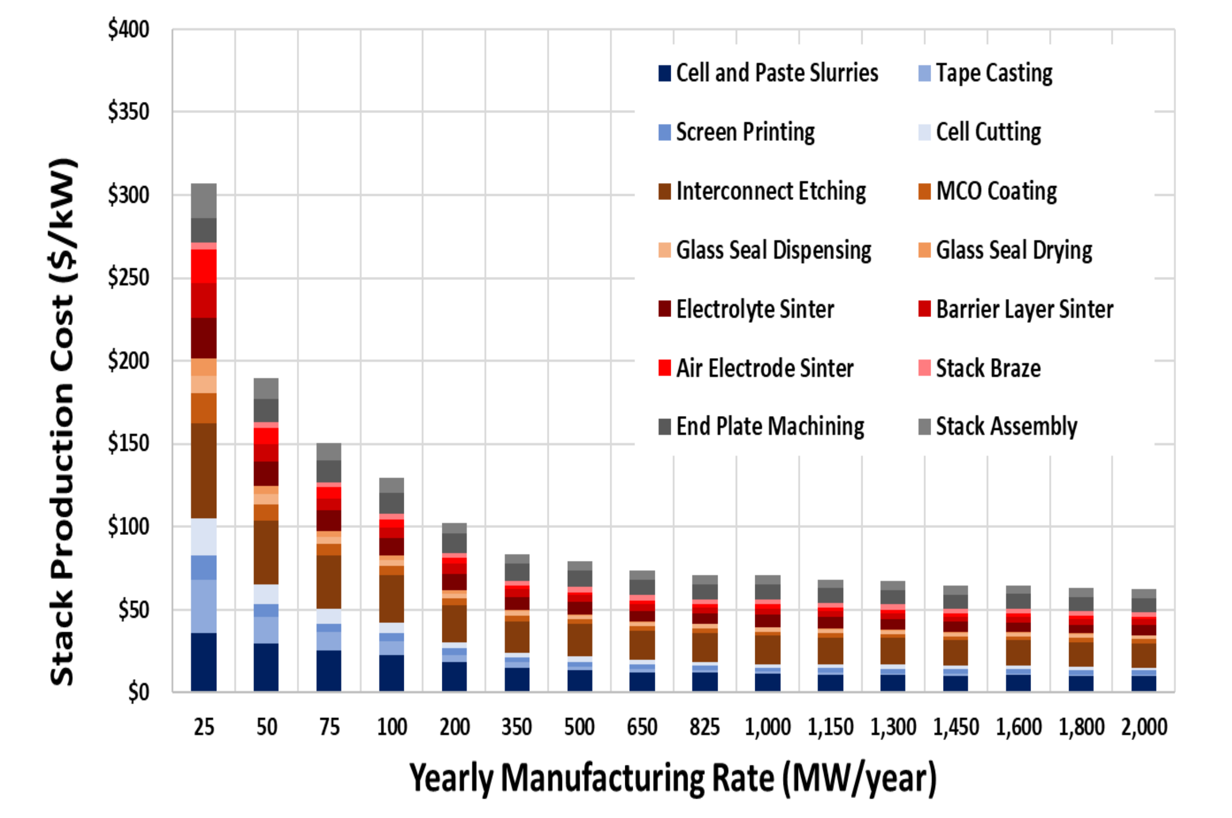
- **Dramatic cost reduction from 25MW/yr to 1 GW/year**
  - Cost reduction above 500MW/yr is modest
- **Material cost & Manufacturing cost are 80% of total cost**
  - Manufacturing is ~50% at low production rates, Materials is ~ 50% at high production rates

SOE TOTAL STACK COST DISTRIBUTION

Excl. contingency

(Broken down by Processing Steps)





Electrolyte-supported Cells (EsC) — **H_2 Electrode-supported Cells (HEsC)**

- Interconnect cost and Cell/Paste Slurries are the two dominant cost contributors
  - Both are primarily material cost contributions

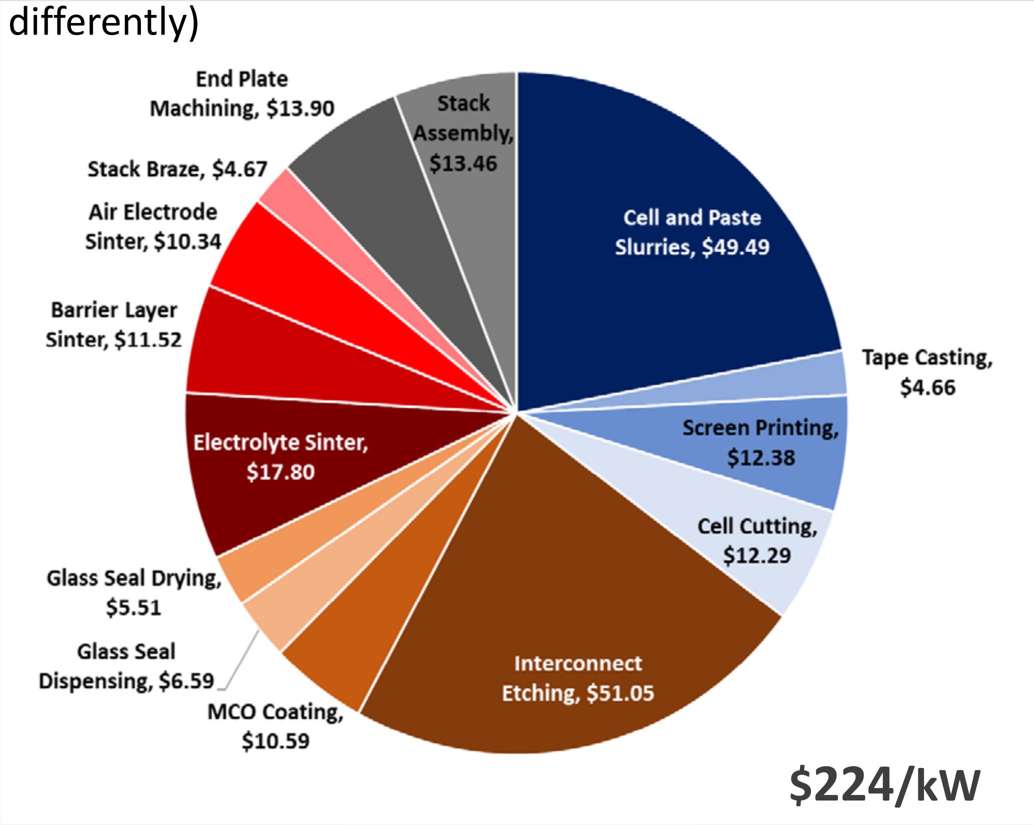
SOE TOTAL STACK COST DISTRIBUTION

Excl. contingency

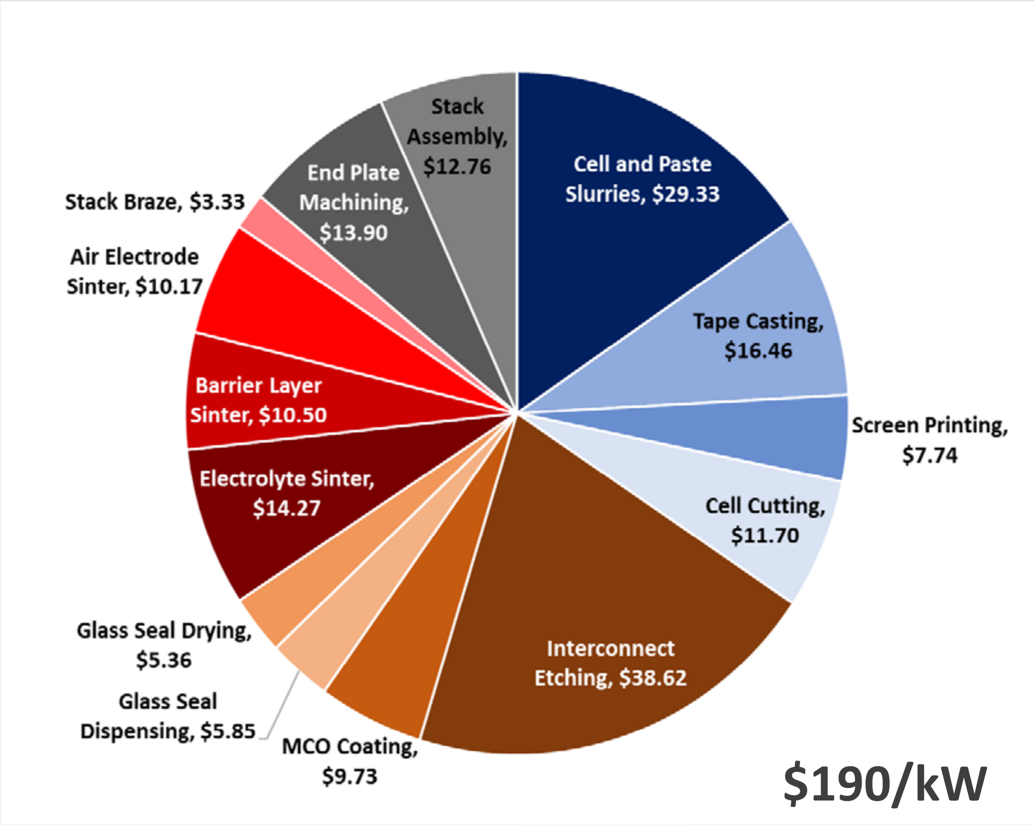
(Broken down by Processing Steps (showing sum of Materials & Manufact.))

(Same data as the previous page, just graphed differently)

50 MW/Year, $/kW



Electrolyte-supported Cells (EsC)



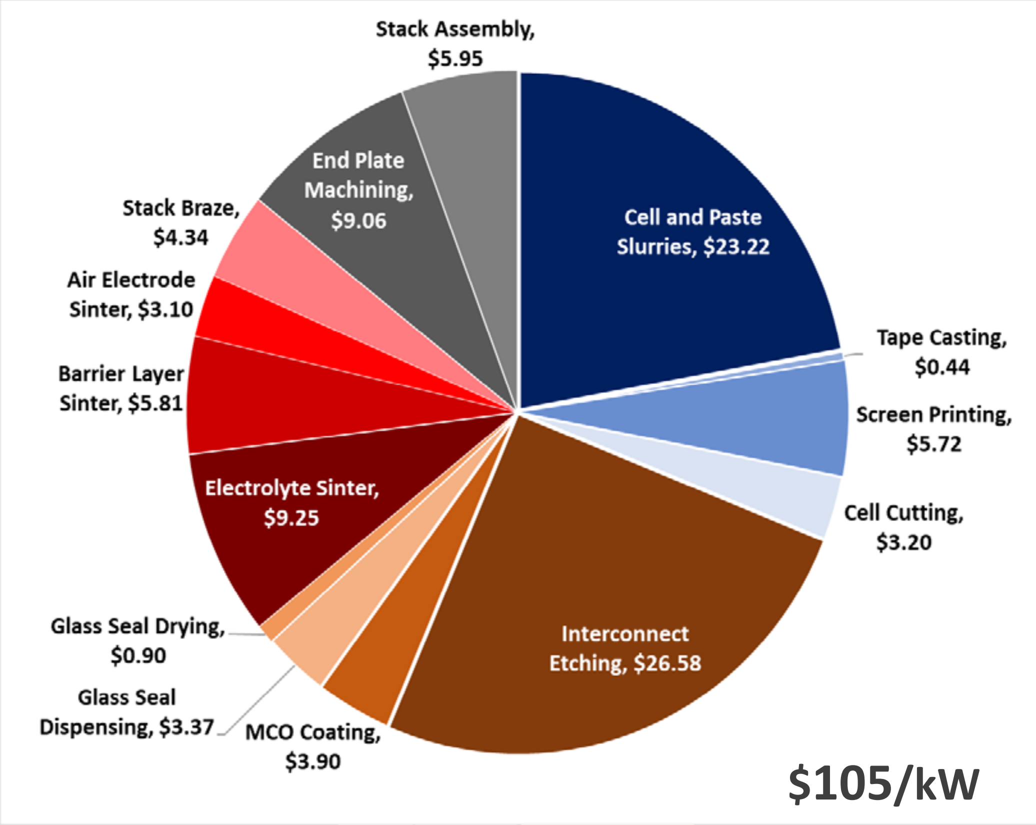
H_2 Electrode-supported Cells (HEsC)

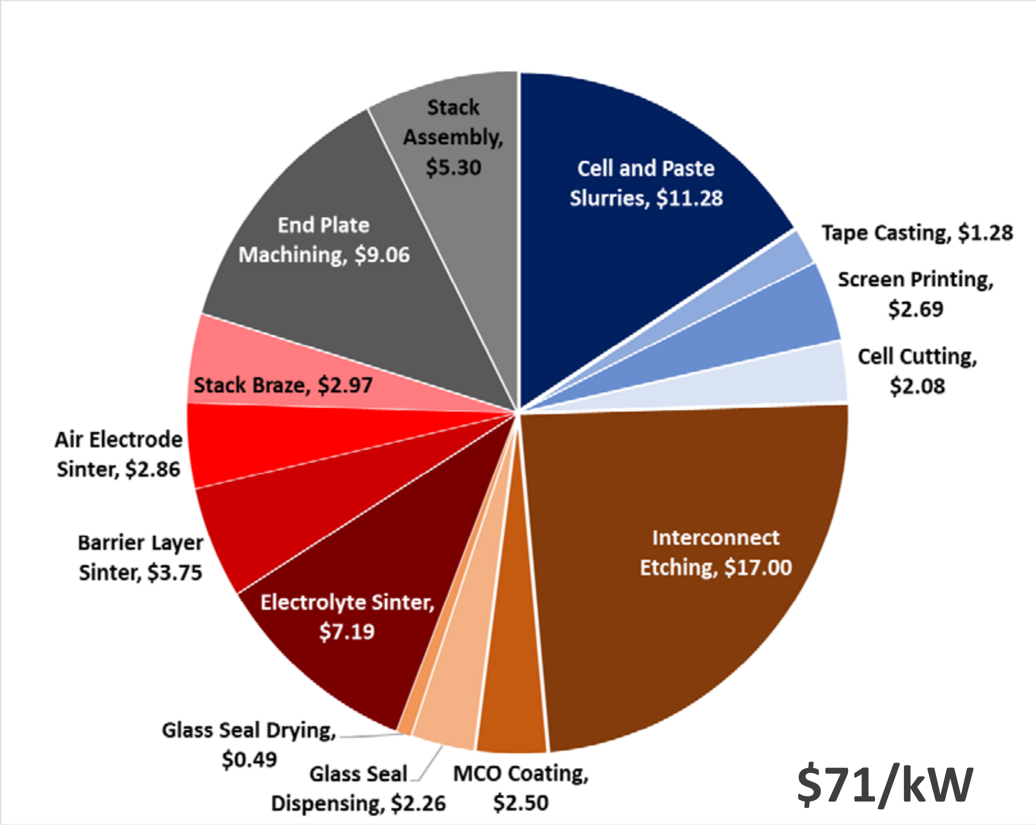
SOE TOTAL STACK COST DISTRIBUTION

Excl. contingency

(Broken down by Processing Steps (showing sum of Materials & Manufact.))

1 GW/Year, $/kW





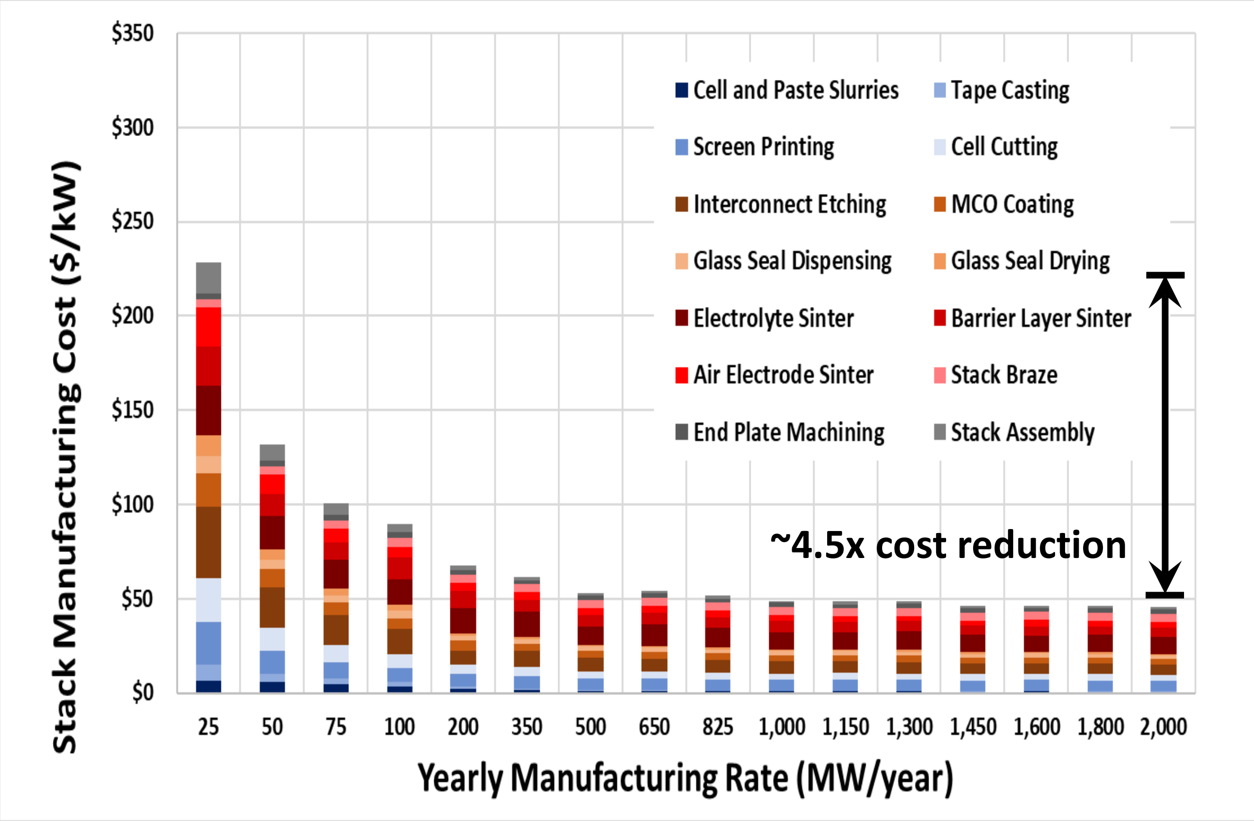
Electrolyte-supported Cells (EsC)

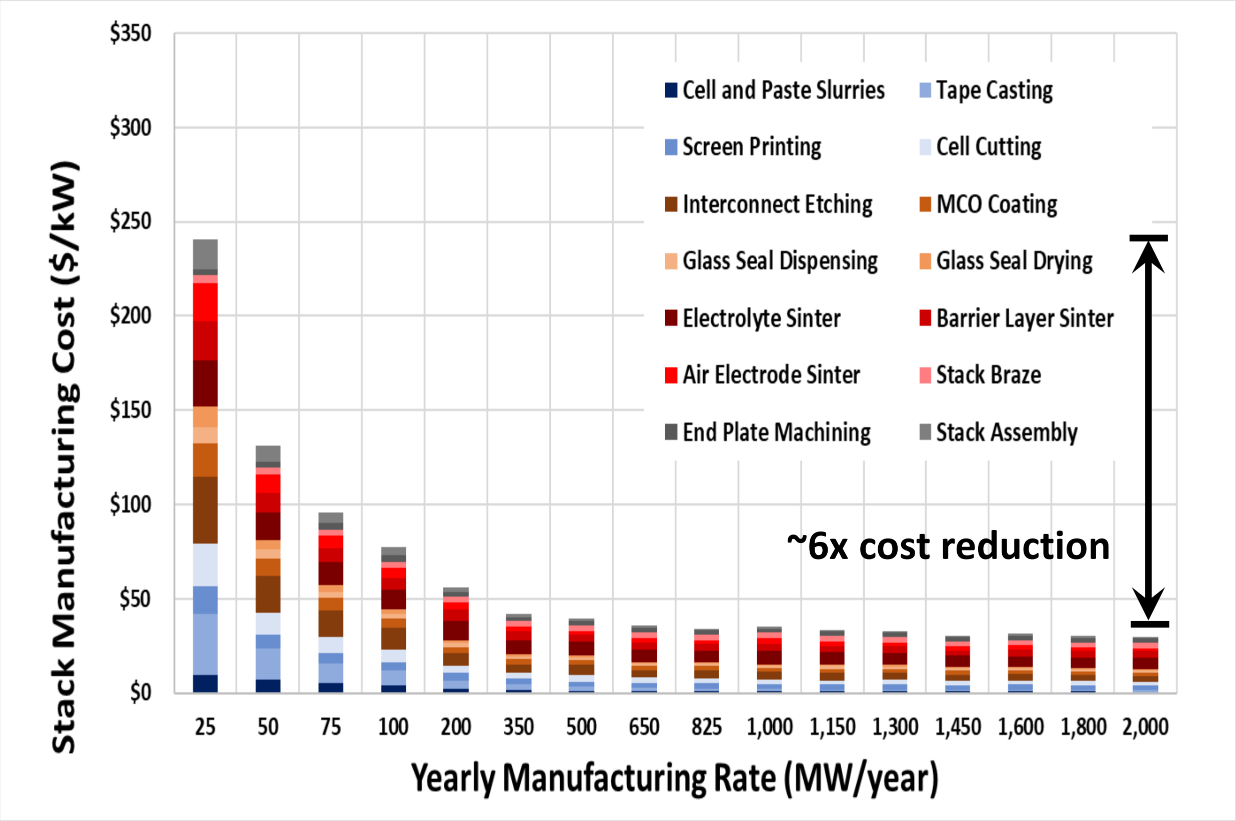
H_2 Electrode-supported Cells (HEsC)

SOE STACK MANUFACTURING COST DISTRIBUTION

Excl. contingency

Excludes Material but includes manufacturing (capital amortization, tooling, labor)





Electrolyte-supported Cells (EsC) **H_2 Electrode-supported Cells (HEsC)**

- ~5x cost reduction between 25MW/yr and 1GW/yr

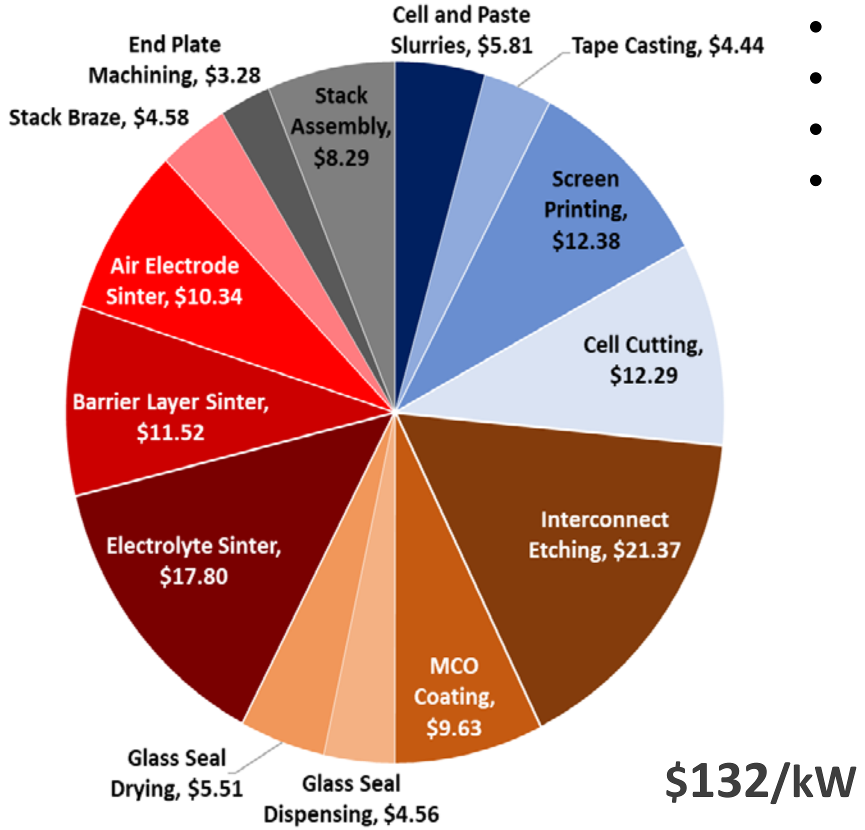
SOE STACK MANUFACTURING COST DISTRIBUTION

Excl. contingency

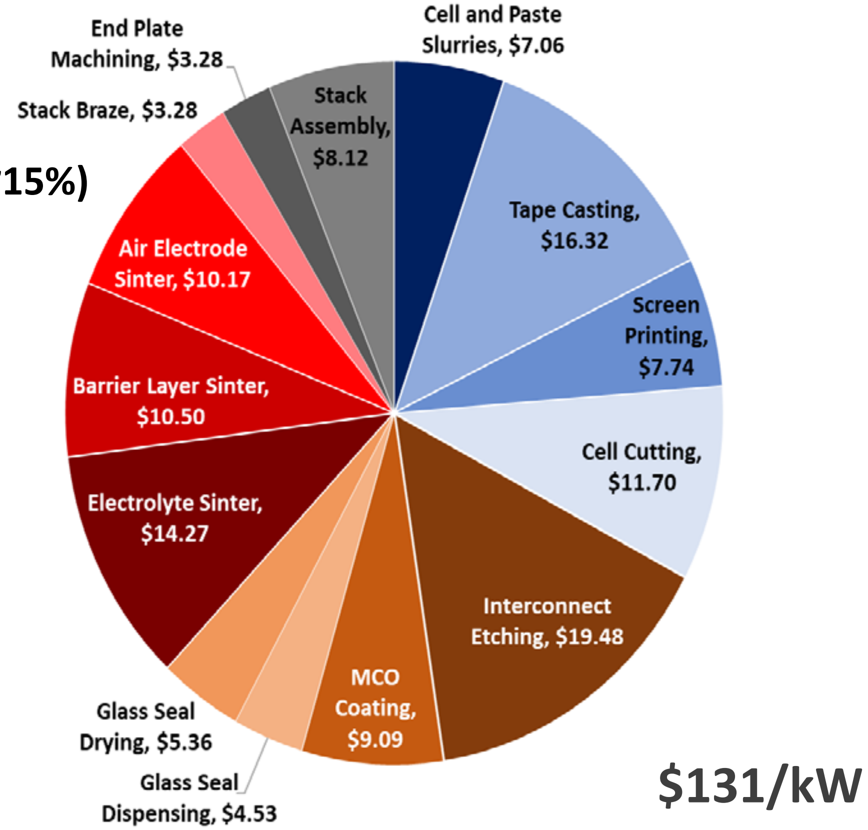
Excludes Material but includes manufacturing (capital amortization, tooling, labor)

50 MW/Year, $/kW

Most significant costs:
- **Heat Treatments (~40%)**
- **Tape Cast (~10%)**
- **Screen Print (~5-10%)**
- **Interconnects (etching) (~15%)**



Electrolyte-supported Cells (EsC)



H_2 Electrode-supported Cells (HEsC)

SOE STACK MANUFACTURING COST DISTRIBUTION

Excl. contingency

Excludes Material but includes manufacturing (capital amortization, tooling, labor)

50 MW/Year, $/kW

Most significant costs:

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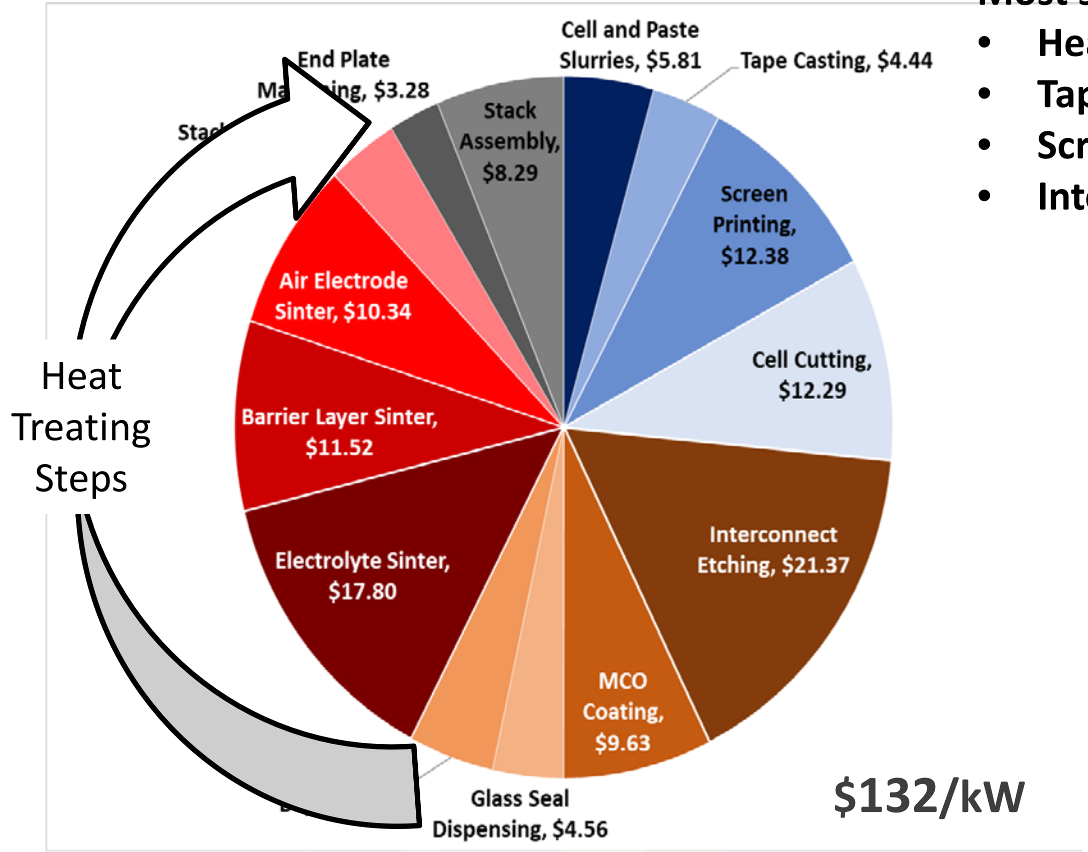
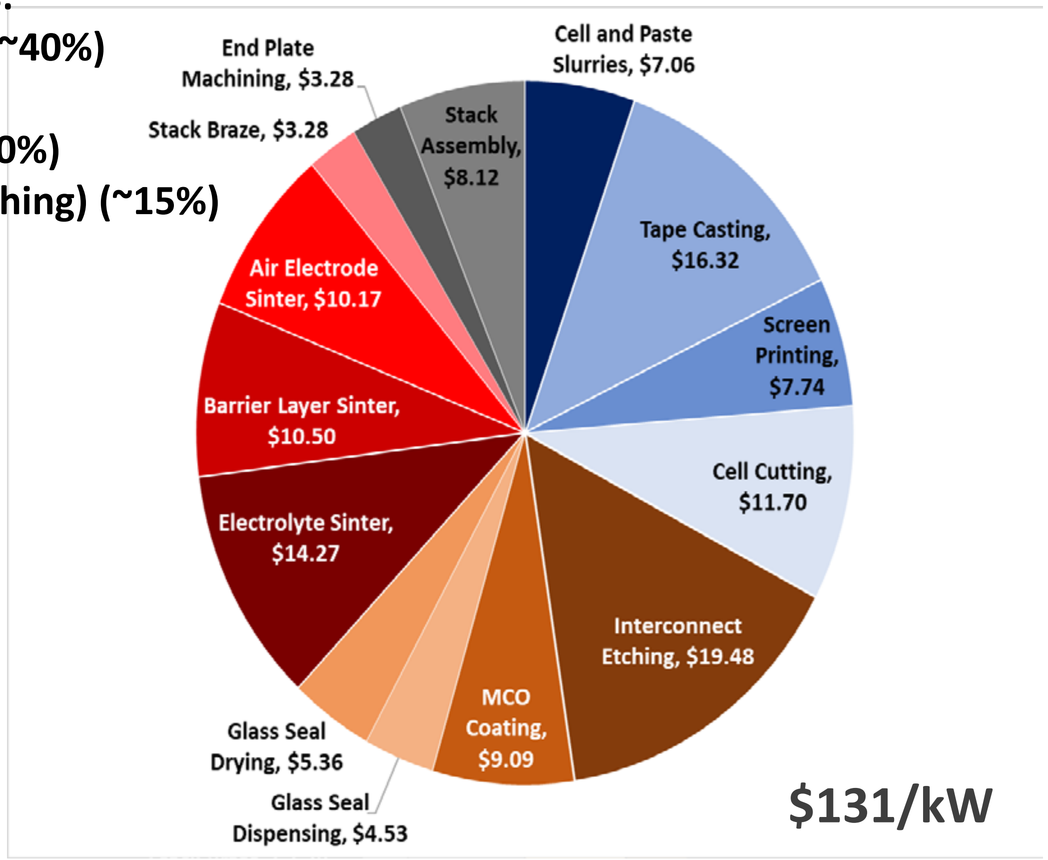


Electrolyte-supported Cells (EsC)



H_2 Electrode-supported Cells (HEsC)

SOE STACK MANUFACTURING COST DISTRIBUTION

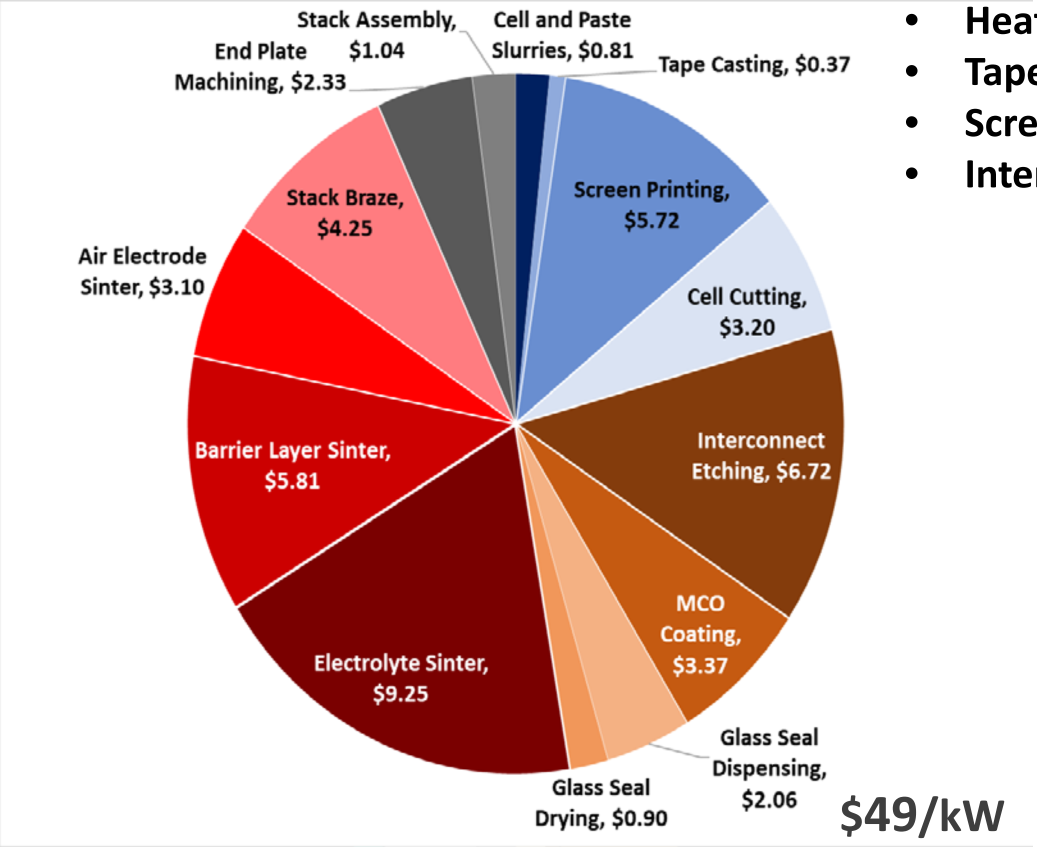
Excl. contingency

Excludes Material but includes manufacturing (capital amortization, tooling, labor)

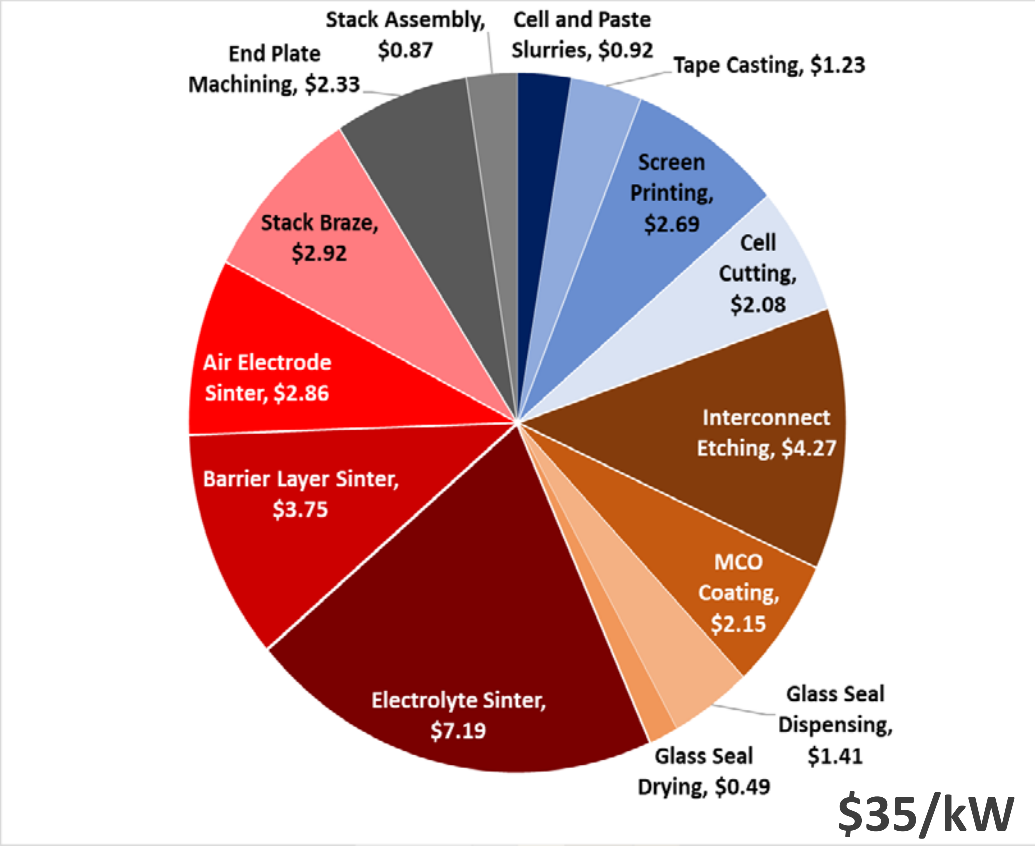
1 GW/Year, $/kW

Most significant costs: (Same as 50MW/yr)

- **Heat Treatments**
- **Tape Cast**
- **Screen Print**
- **Interconnects (etching)**



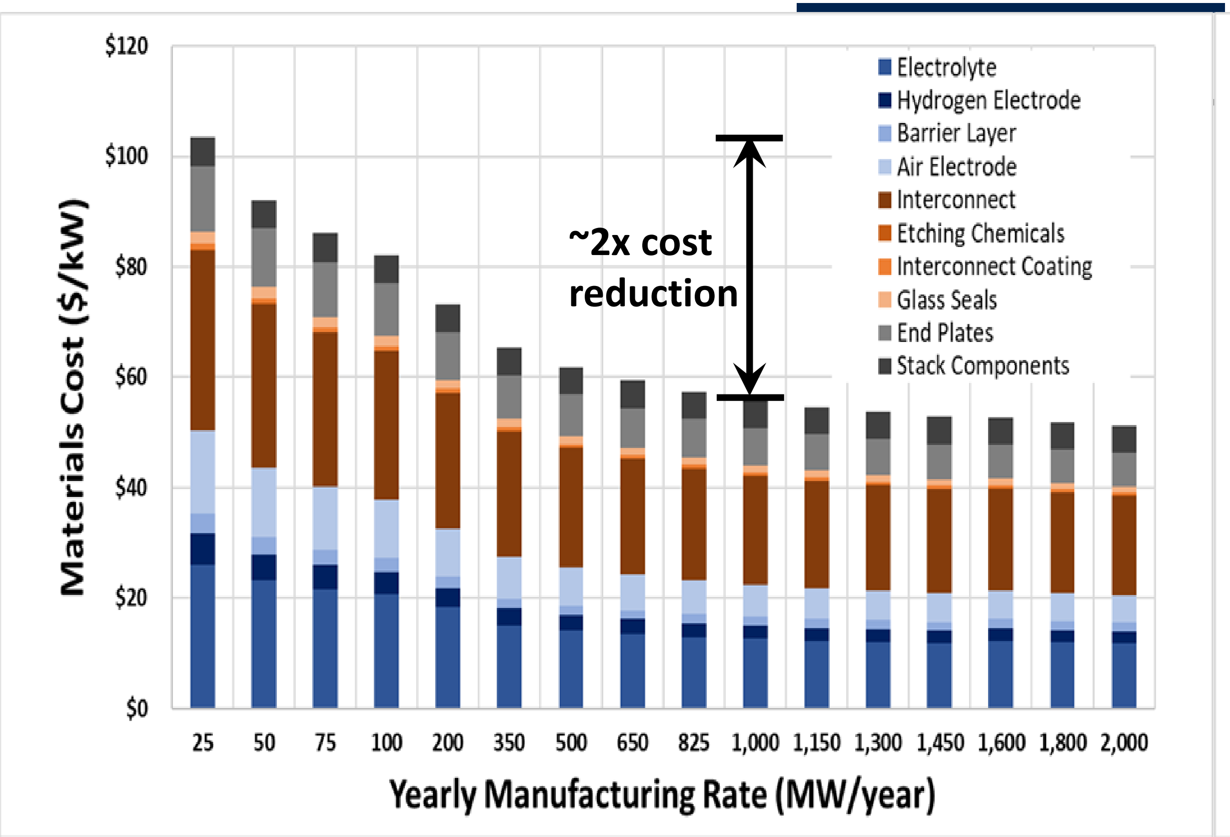
Electrolyte-supported Cells (EsC)



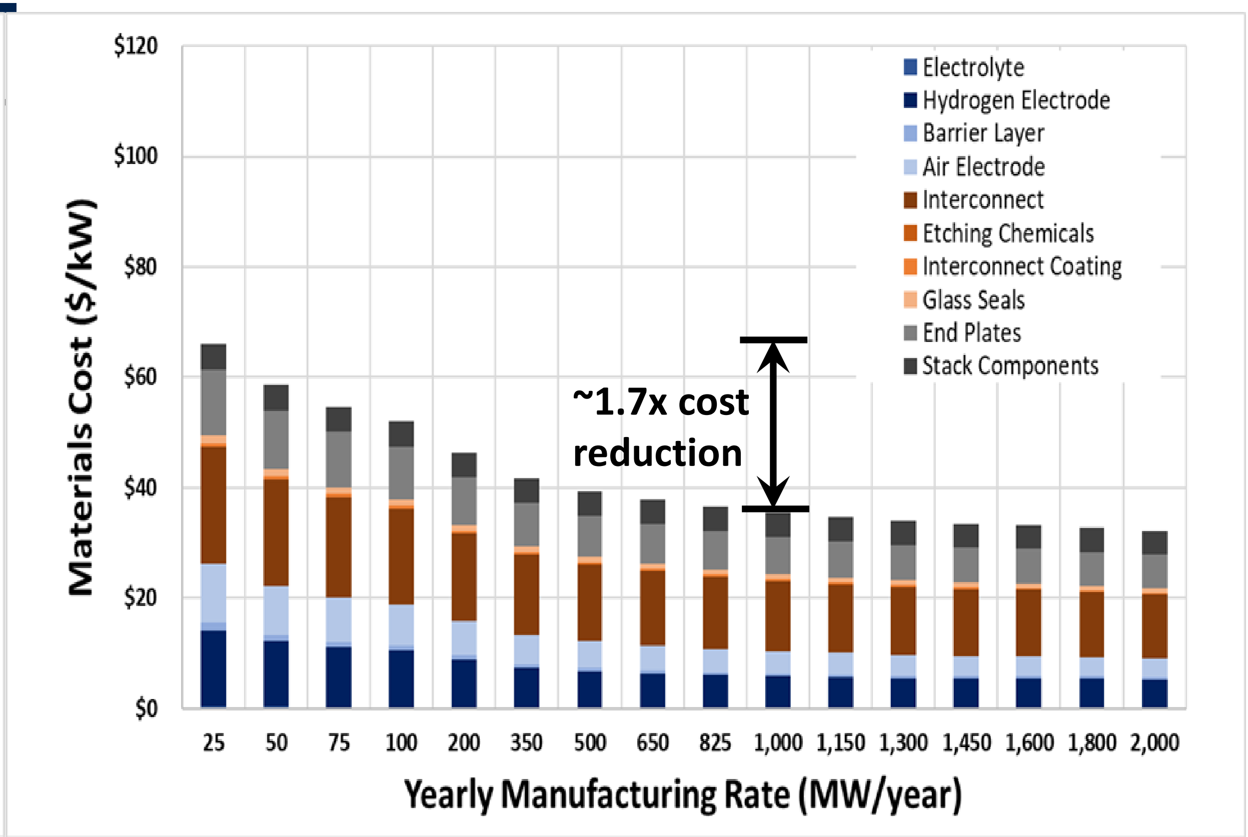
H_2 Electrode-supported Cells (HEsC)

SOE STACK MATERIAL COST DISTRIBUTION

Excl. contingency



Electrolyte-supported Cells (EsC)



H_2 Electrode-supported Cells (HEsC)

- (Only) ~2x material cost reduction is expected between 25MW/yr and 1GW/yr
- HEsC material cost significantly lower than EsC material cost
  - Primarily due to the power density improvement (900mW/cm^2 vs. 1500mA/cm^2, at 1.285V/cell)

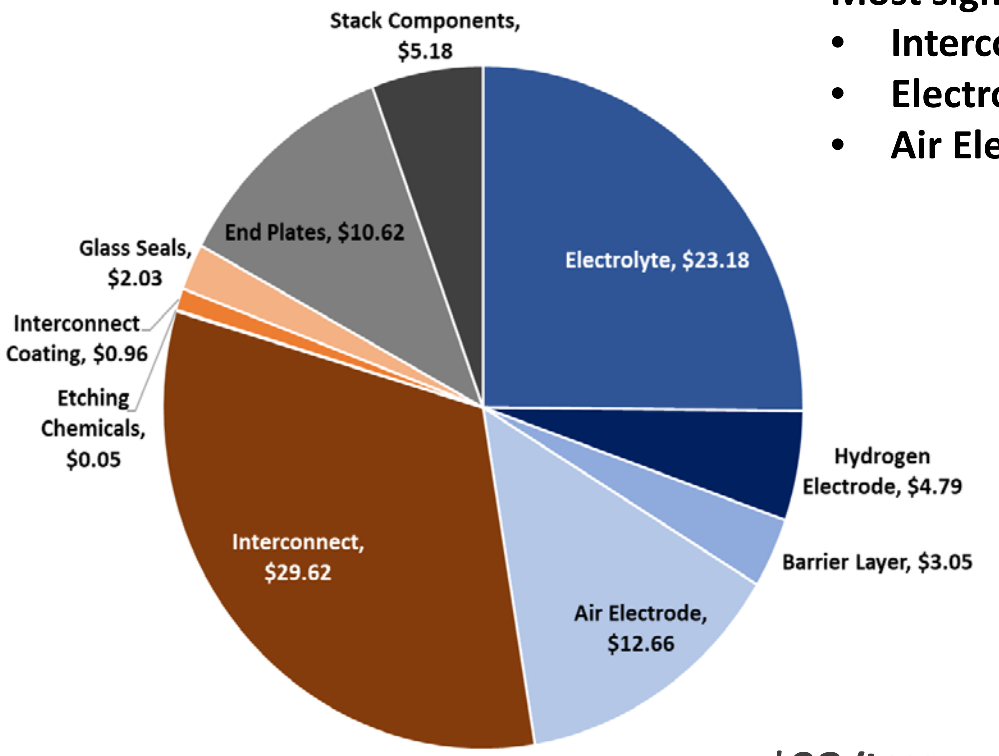
SOE STACK MATERIAL COST DISTRIBUTION

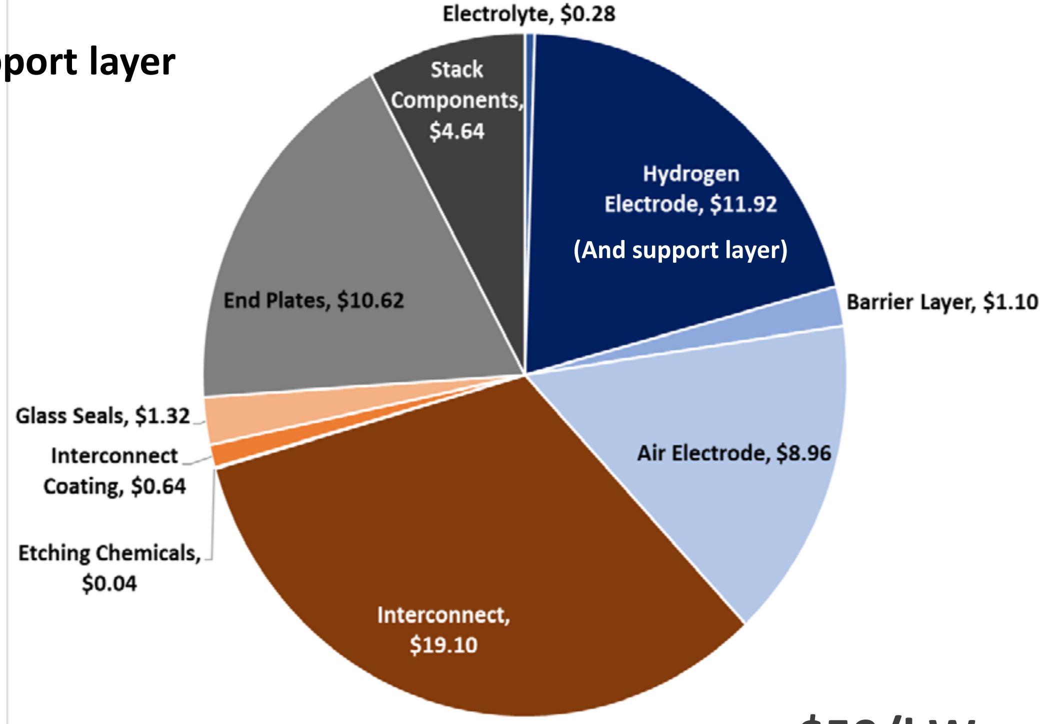
Excl. contingency

50 MW/Year, $/kW

Most significant costs:

- **Interconnects**
- **Electrolyte/Support layer**
- **Air Electrode**





Electrolyte-supported Cells (EsC)

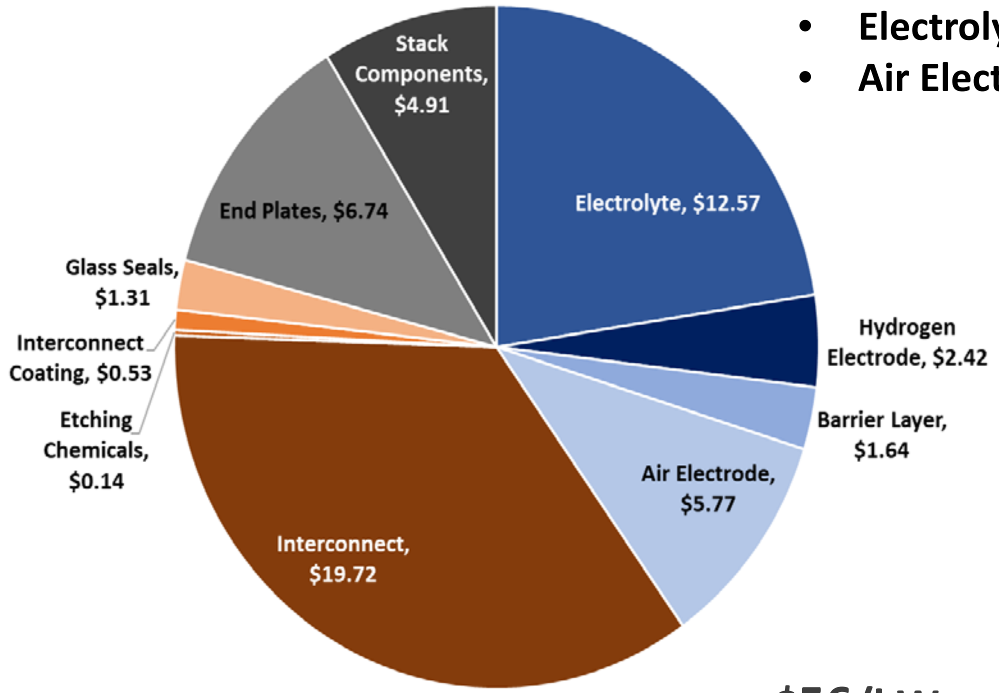
H_2 Electrode-supported Cells (HEsC)

SOE STACK MATERIAL COST DISTRIBUTION

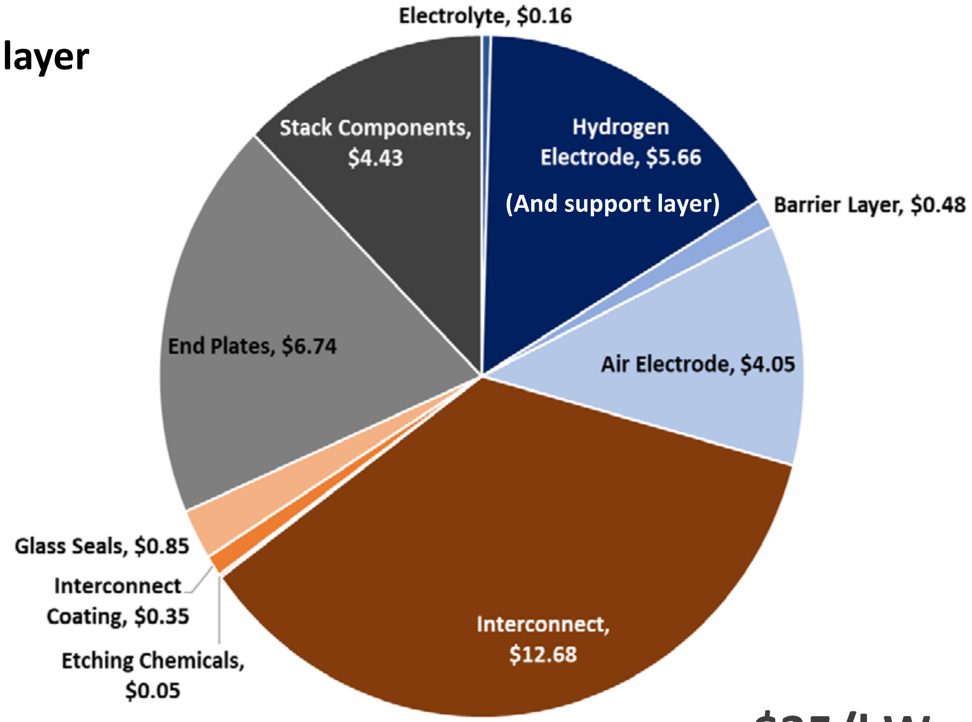
Excl. contingency

1 GW/Year, $/kW

Most significant costs: (same as 50MW/yr)
- **Interconnects**
- **Electrolyte/Support layer**
- **Air Electrode**



$56/kW

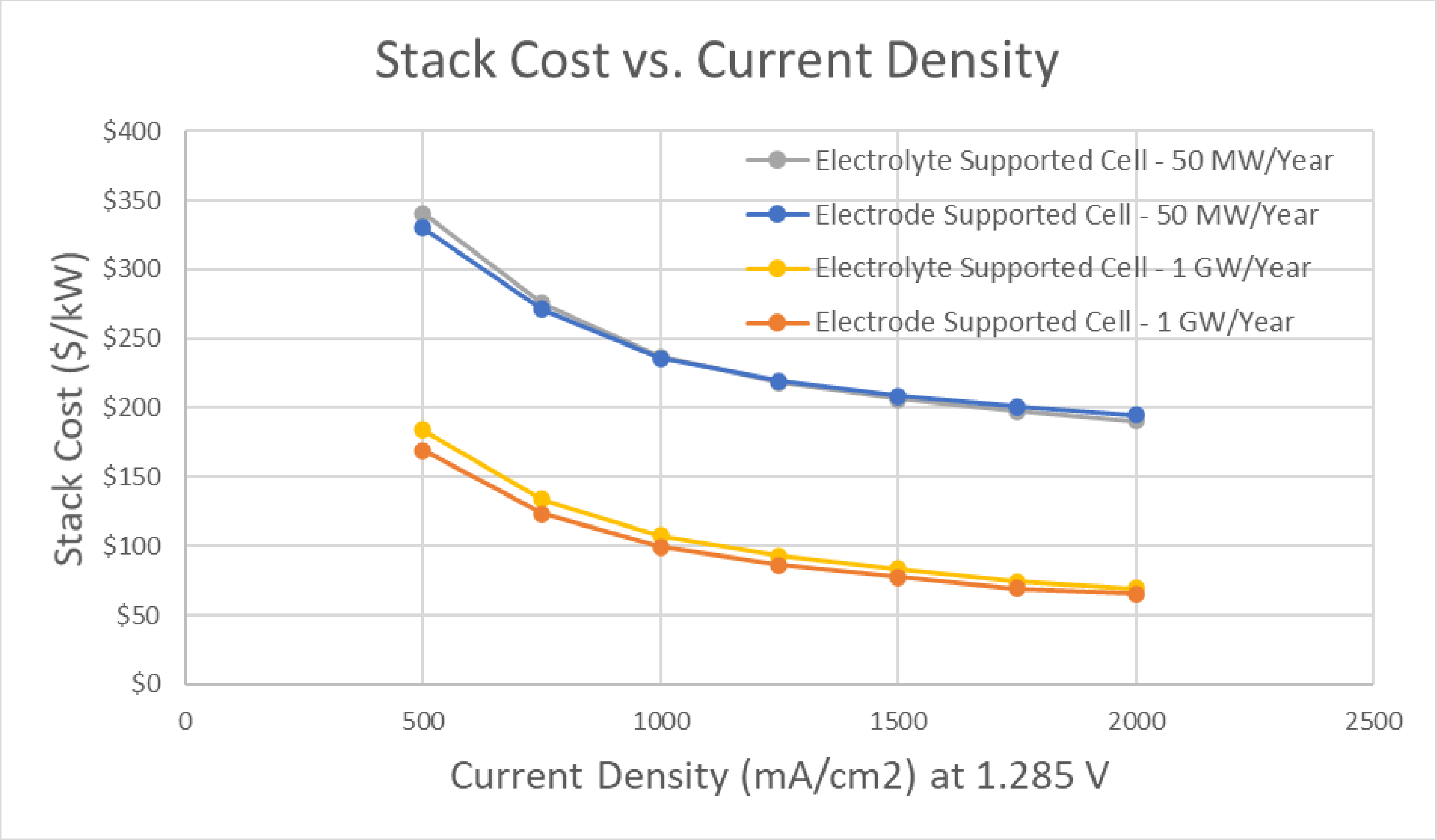


$35/kW

Electrolyte-supported Cells (EsC)

H_2 Electrode-supported Cells (HEsC)

TOTAL COST VARIATION WITH POWER DENSITY

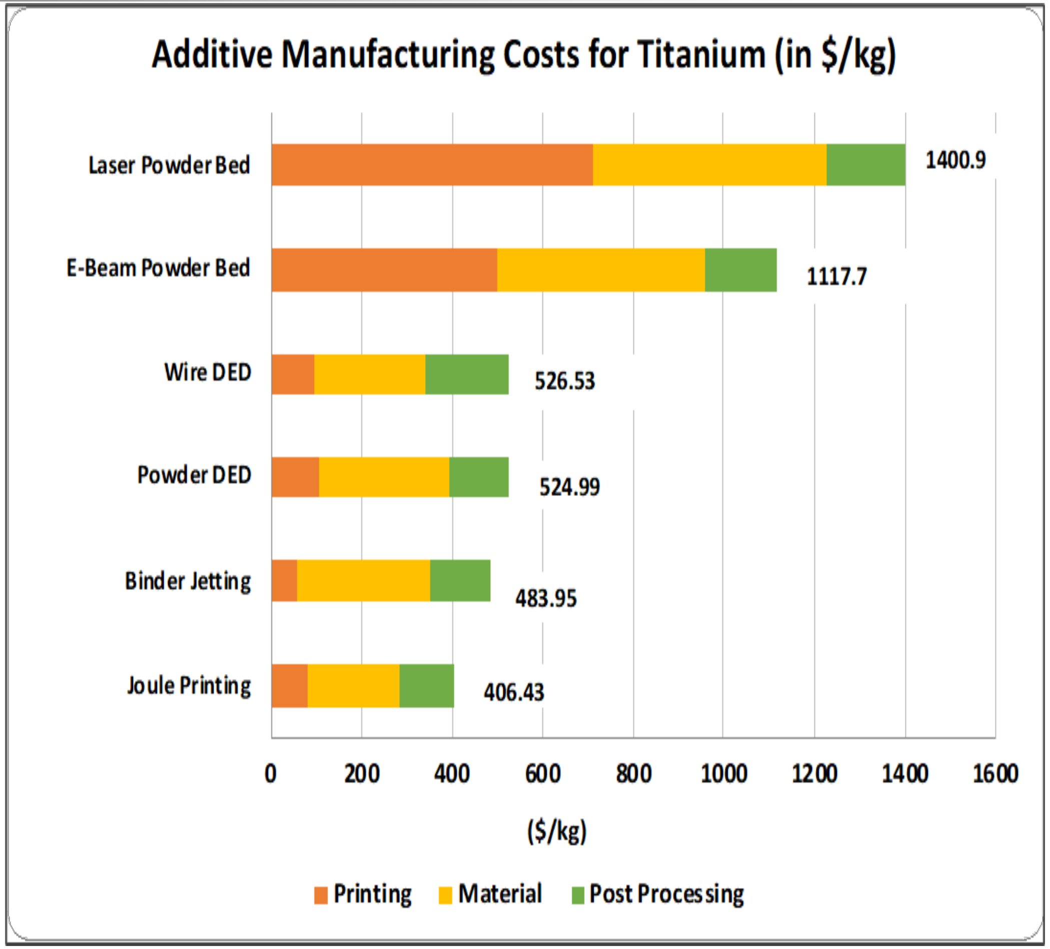


- **Improved current-density/power-density reduces stack cost (obvious)**
- **EsC and HEsC are very similar cost on a $/cm² basis (less obvious)**
  - **Largest cost difference is that granted by an improvement in current density (HEsC 1500 vs. EsC 900 mA/cm²)**

SOEC ADDITIVE MANUFACTURING OPPORTUNITIES

Additive Manufacturing vs. Conventional Multi-Step Processing

- **Near-Net shape Additive Manufacturing**
  - cost-effective automated manufacturing
  - geometrically complex electrochemical ceramics laminations and devices (57% improvement in cell performance and in voltage degradation for corrugated layers)
- **Multiple Approaches** provide good surface finish and dimensional precision
  - Ink jet AM printing (most common in corrugated surface applications)
  - Stereolithography (SLA)
  - Digital Light Processing (DLP) for resin curing
- **Cost Competitiveness**: Total cost and the share of major cost categories vary by material, AM mfg. and material – Joule Printing for Ti AM

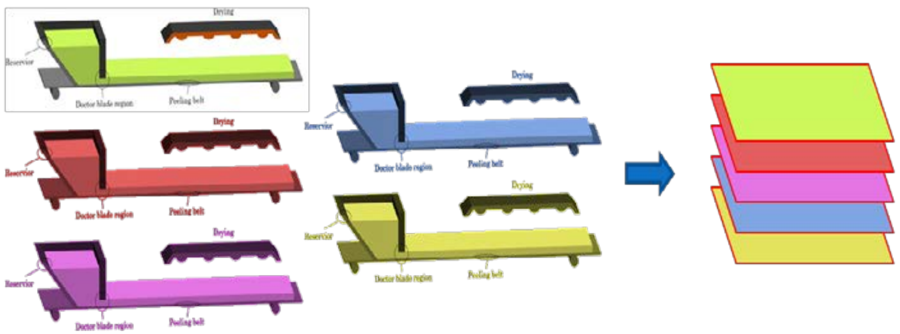


Source: https://medium.com/@alexhuckstepp/economics-of-metal-additive-manufacturing-f1efd17dce2d

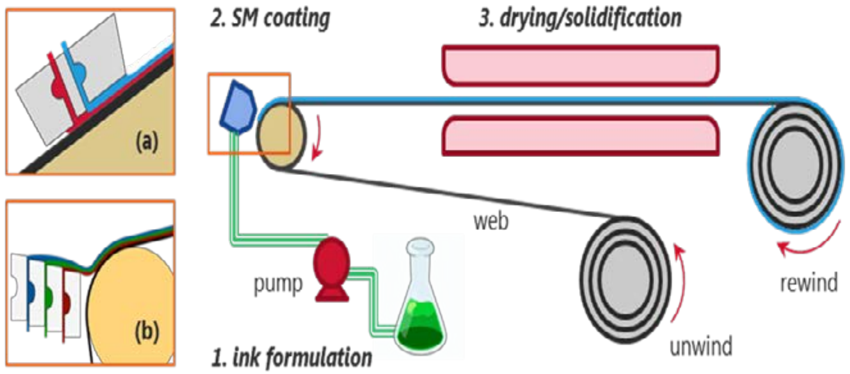
SOEC ROLL-TO-ROLL MANUFACTURING OPPORTUNITIES

- **<u>Roll-to-Roll manufacturing</u>** facilitates is a cost-effective streamlined continuous manufacturing route for solid-state electrochemical devices
- **<u>Simultaneous multi-layer co-coating</u>** (up to six layers at a time supported by DOE/AMO)
  - Enables finer-grained thinner films at a lower cost than laminated films
  - Cost-effectiveness of other major expensive process steps such as thermal treatment beyond the initial multi-layer coating step will be important for its overall economic viability

Current practice: Single layer slot or tape casting (knife)



Next generation: Simultaneous multilayer coating



<u>Source:</u> Peet, J. (2019). "Development of Roll-to-Roll Simultaneous Multilayer Deposition Methods for Solid-State Electrochemical Devices Using Highly Particulate Loaded Aqueous Inks," ," U.S. DOE Advanced Manufacturing Office Program Review Meeting, Washington, DC, June 11-13.

Possible Cost Reduction Strategies
(Process simplification, parts & step count reduction!)

- **Sizing-Up**
  - Higher Production Rates/Capacity (GW-scale)
  - Larger cell active area
  - Larger Stacks (>50kW)
  - Leverage existing SOFC manufacturing capacity
- **Manufacturing/Process-Development**
  - Multilayer/R2R printing of material layers
  - Co-firing/Reduced-number-of firing
  - Improved/Optimized Glass Seal Firing
  - Optimized cycle times and Tight Furnace Packing
  - Plasma Sintering (improv. energy effic., faster cycle
  - Larger Batch Sizes for materials processing/Heat Treatments (Continuous vs. Batch)
  - Rapid catalyst application/infiltration
  - Increased/Faster robotic handling
- **Operations/Performance**
  - Lower/Higher Pressure
  - Lower Operating Temp. for lower-cost metal alloys
  - Higher Power Density
  - Higher Steam Utilization
  - Lower/No Air Sweep Rate
- **Balance of Plant**
  - Compact/Low-Cost Heat Exchangers
  - Improved power electronics (inverters)
    - Higher voltage, higher efficiency
  - Lower cost SS alloy (rather than Nickel-based alloys)
  - Streamlined on-site installation
- **Other**
  - Oxygen sales
  - Grid capacity payments

Thank You!

Questions?

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